

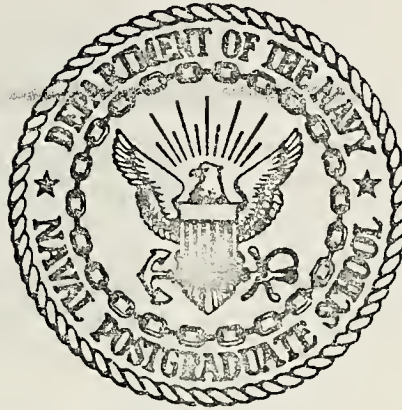
THE PULSEJET ENGINE
A REVIEW OF ITS DEVELOPMENT POTENTIAL

John Grant O'Brien

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THESIS

THE PULSEJET ENGINE
A REVIEW OF ITS DEVELOPMENT POTENTIAL

by

John Grant O'Brien

June 1974

Thesis Advisor:

M.F. Platzer

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of pulsejets for auxiliary power generation, and attempts to use a pulsejet as a combustor for a gas turbine engine.

This paper reviews this recent work and includes thermodynamic analysis, a description of wave processes, and a description of the ignition mechanism. The problems of noise and vibration are also addressed. From this study of recent work, several potential applications are proposed, and recommendations about areas requiring further study are made.

The Pulsejet Engine
A Review of its Development Potential

by

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Lieutenant Commander, United States Navy
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ABSTRACT

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This paper reviews this recent work and includes thermodynamic analysis, a description of wave processes, and a description of the ignition mechanism. The problems of noise and vibration are also addressed. From this study of recent work, several potential applications are proposed, and recommendations about areas requiring further study are made.

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LIST OF SYMBOLS

$$a = \frac{m}{m-1}$$

$$b = \frac{n}{n-1}$$

B = temperature ratio function

C_P = specific heat at constant pressure

C_V = specific heat at constant volume

c = speed of sound

E = temperature and pressure ratio function

E_f = chemical energy of fuel

f = fuel/air ratio

h = specific enthalpy

m = polytropic parameter of combustion

n = polytropic parameter of expansion

P = pressure

q = heat per unit mass

Q_f = heating value of the fuel

R = gas constant

T = temperature

U_f = internal energy

v = specific volume

W = work

α = efficiency factor for pressure gain combustor

β = air mass ratio

γ = ratio of specific heat, C_P/C_V

η = efficiency

Π = pressure ratio and/or temperature ratio in
constant volume process

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I. INTRODUCTION

The pulsejet engine found a brief, but truly surprising and shocking application during World War II when the German V-1 buzz bombs suddenly appeared over London in 1944. Since then, the pulsejet has largely been an engine of frustrated expectations even though several attempts have been made to develop this propulsion concept further. In the past few years new work has been initiated in this field, mostly outside of the United States. It is the purpose of the present report to review these activities and to assess the development potential of this fascinating, low cost propulsion device.

II. PRINCIPLE OF OPERATION

A pulsejet is a surprisingly simple propulsive device, with few or no moving parts, which is capable of producing thrust from a standing start to a relatively high velocity, of the order of Mach 1.5. Essentially, it is a tube open at one end and fitted at the other end with either mechanical or aerodynamic valves (figs. 1 and 2).

When a fuel/air mixture is injected into the combustion chamber it is initially ignited by a spark and a high pressure is developed which forces the hot gases to be discharged. Due to the inertia of the exhaust gases, the combustion chamber is partially evacuated allowing the inflow of a new charge through the valves. At the same time, air is also sucked in through the tail pipe toward the combustion chamber. This new charge is then ignited by residual hot gases and the process repeats itself. Thus an operating cycle is created that consists basically of intake, combustion, expansion, and exhaust.

The question then is, "What thermodynamic cycle best represents the operation of a pulsejet?" The processes in the Lenoir engine, an early two-stroke piston engine without precompression, are quite similar to the processes occurring in the pulsejet and, therefore, the Lenoir cycle serves as a good model for the thermodynamic analysis of a pulsejet. The Lenoir engine (fig. 3) has intake during the first half

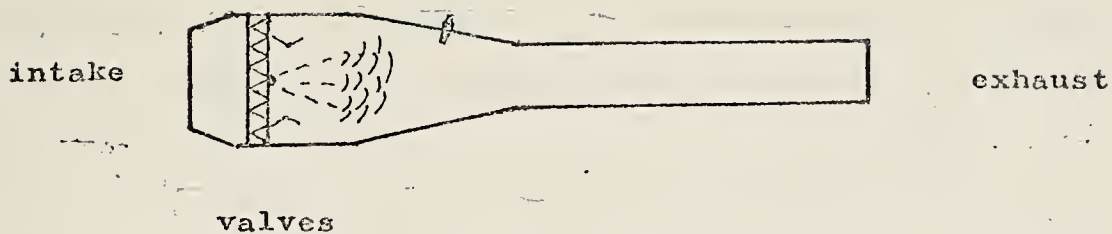


Figure 1. Typical pulsejet with mechanical valves.

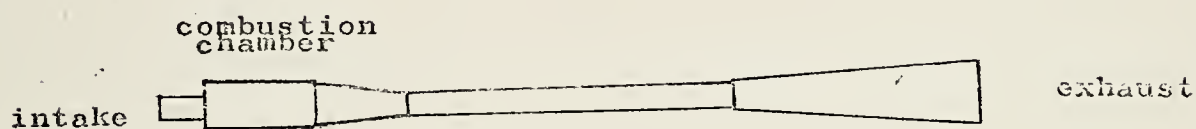


Figure 2. Typical pulsejet with aerodynamic valves.

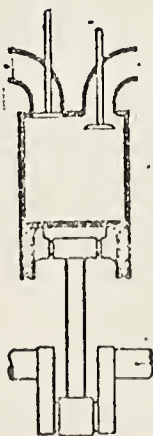


Figure 3. The Lenoir engine. (2)

of the downstroke, ignition at approximately the half-way point, and then expansion for the remainder of the downstroke. Exhaust takes place at constant pressure during the upstroke.

III. HISTORY

It has been recognized for some time that constant volume combustion has the potential of improved thermal efficiency when compared with constant pressure combustion. The first work on pulsating combustion appeared in France in the early twentieth century and was applied to gas turbine combustion chambers. One of these chambers developed by Karavodine is shown in figure 4. It consisted of water cooled explosion chambers and the jet flow out of these explosion chambers drove a turbine wheel. The combustion pressures were rather low and as a result the specific fuel consumption was quite unfavorable.

Esnault-Pelterie used two explosion chambers (fig. 5) which worked in phase opposition and thus achieved a more continuous outflow through the nozzle and onto the turbine wheel. In 1909 Marconnet first proposed the use of pulsating combustion for aircraft jet propulsion. His configuration is shown in figure 6. Note that no mechanical valves were used in Marconnet's device and it thus was remarkably close to modern configurations.

All of these ideas apparently came too early for practical aircraft applications and were soon forgotten. Only twenty years later Paul Schmidt [1] independently proposed the configuration shown in figure 7 which uses mechanical valves. At first, Schmidt used shock waves, which were generated

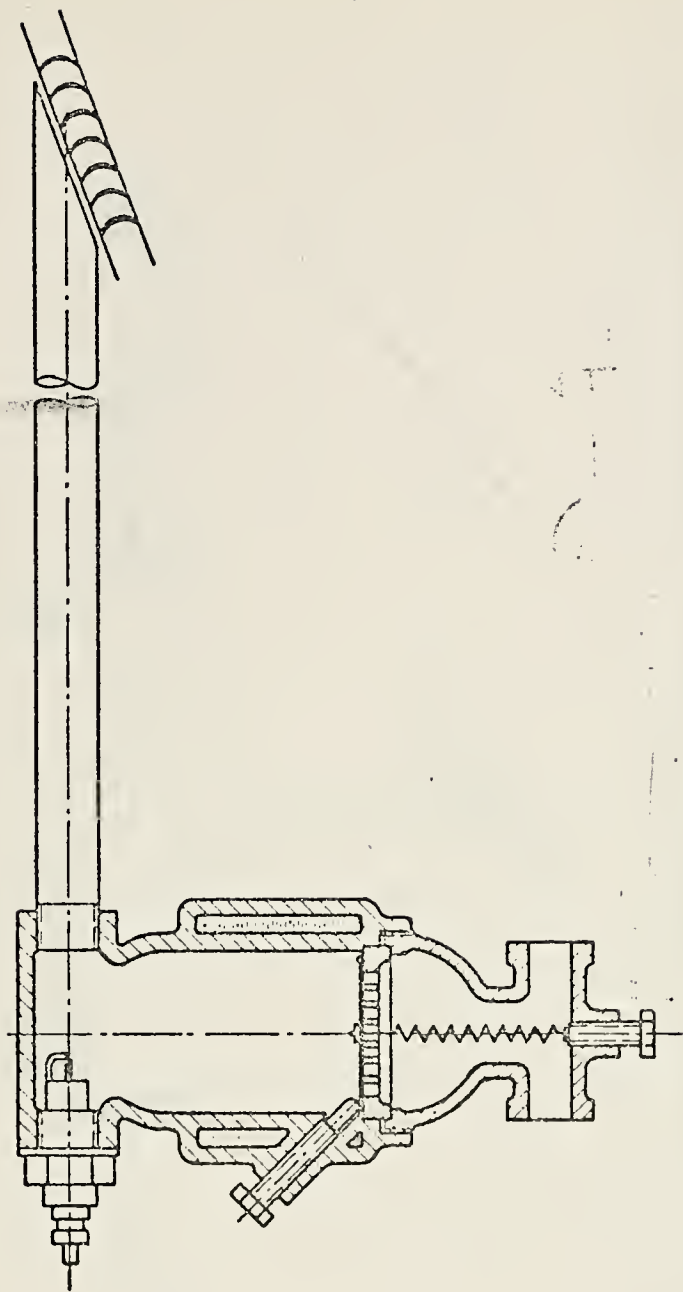


Figure 4. The gas turbine combustion chamber of KARAVODINE. (3)



Figure 6. The pulsejet of MARCONNET, 1909. (3)

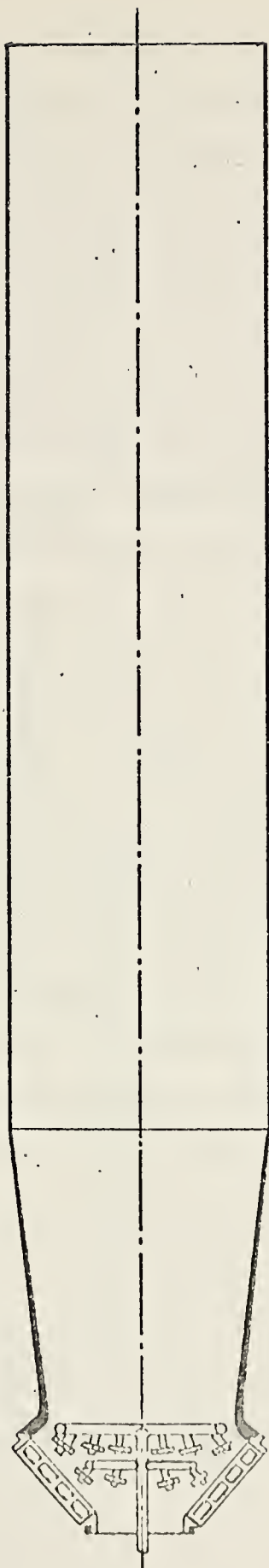


Figure 7. An early pulsejet designed by SCHMIDT. (3)

either by explosions outside the tube or by a piston, to initiate rapid ignition. Later, he found that the tube would work without spark ignition if the valve cross section was properly chosen. The performance potential of the Schmidt-tube was investigated theoretically by Busemann and Schultz-Grunow who came to the conclusion that the efficiency would be relatively low because of the low precompression of the mixture and hence would be inferior to the conventional propellor/piston engine combination, but that the Schmidt-tube would be considerably simpler and lighter. The events of the following years, i.e., World War II in Germany, generated sufficient government support for further development leading to the mass production of this engine by the ARGUS Motor Company. A number of people contributed to the further development of the Schmidt-tube; in particular Diedrich and Staab. Their work is summarized in AGARDograph number 20 [1] where a comprehensive review of this work during WWII in Germany is given.'

In 1933, Reynst [2] discovered a different pulsating combustion phenomenon when he observed that pulsating combustion in a pot-like, water cooled combustion chamber (fig. 8) could be started by spark ignition and then would maintain itself. He experimented with the configuration during the war in Germany and built such a device for the French engine company SNECMA immediately after the war. He proposed a number of applications for this device including

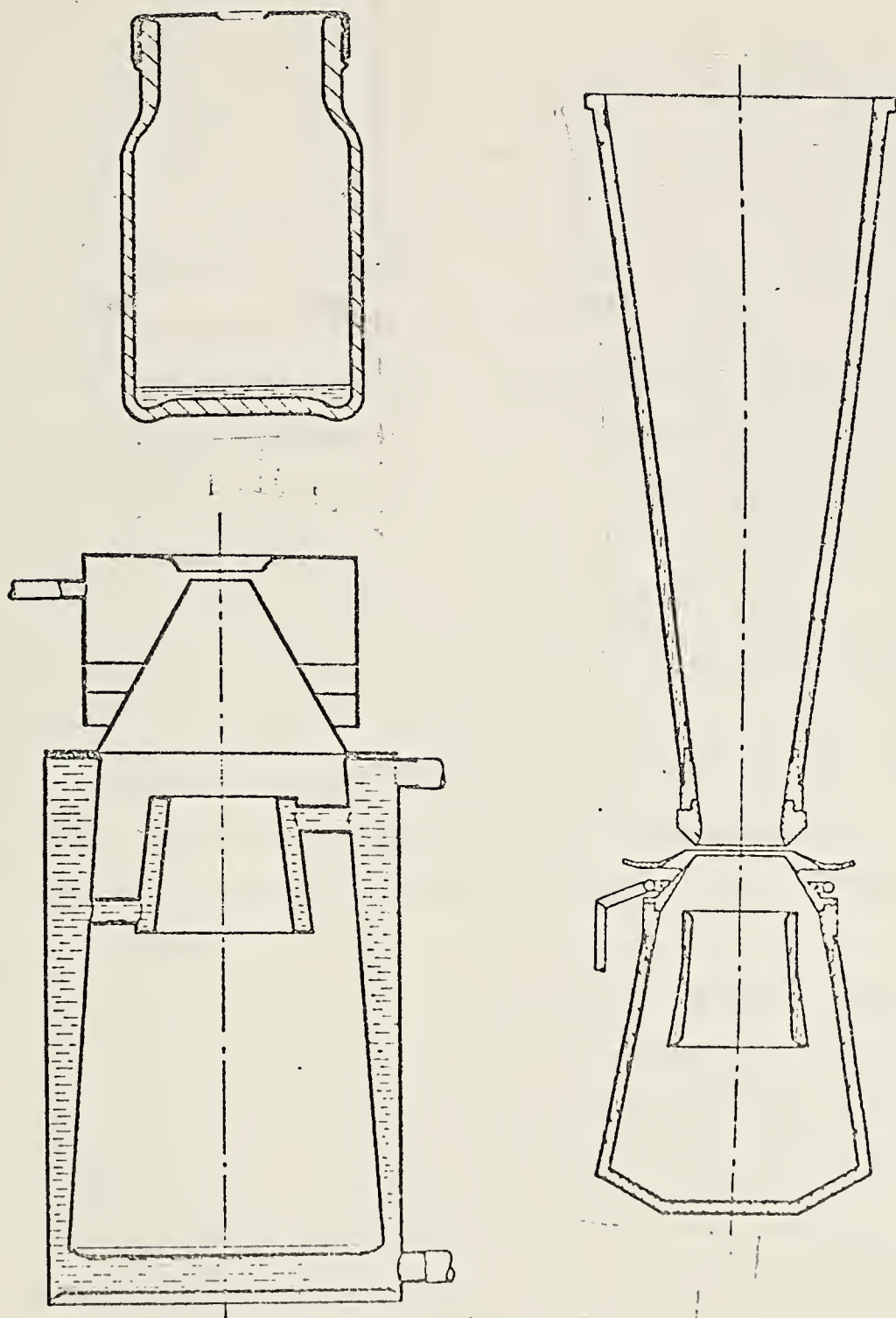


Figure 8. Various versions of REYNST's combustion pot.(3)

aircraft propulsion. These ideas are all summarized in his collected papers [2].

Further independent work on pulsating combustion was started toward the end of WW II in both France and the United States. Bertin [3] in France proposed and developed valveless configurations shown in figures (9a) and (9b) which exhibited amazingly low specific fuel consumption and were later used for sail plane propulsion. In 1944 Schubert [4] at Annapolis started pulsejet work in this country and considerable work was supported in the years immediately after WW II by the U.S. Navy under the code name Project SQUID. In particular, the studies by Foa [3], Rudinger [3] and Logan [3] are worthy of mention. This work is well documented in the Project SQUID proceedings published by the U.S. Navy [4].

These investigations, however, generally led to the conclusion that pulsejet propulsion was inherently inferior to other possible propulsion methods; e.g., turbojet, ramjet, and turboprop.

Further pulsejet research was conducted at Fairchild-Hiller Aircraft Company by R. M. Lockwood who investigated the use of pulsejets as a lift propulsion system [5]. Lockwood found that a pulse reactor engine would not ingest foreign objects more dense than air, that exhaust gas temperature was low enough not to cause a fire hazard, and that such a device could therefore be used in virtually all rough terrain applications.

a)



b)

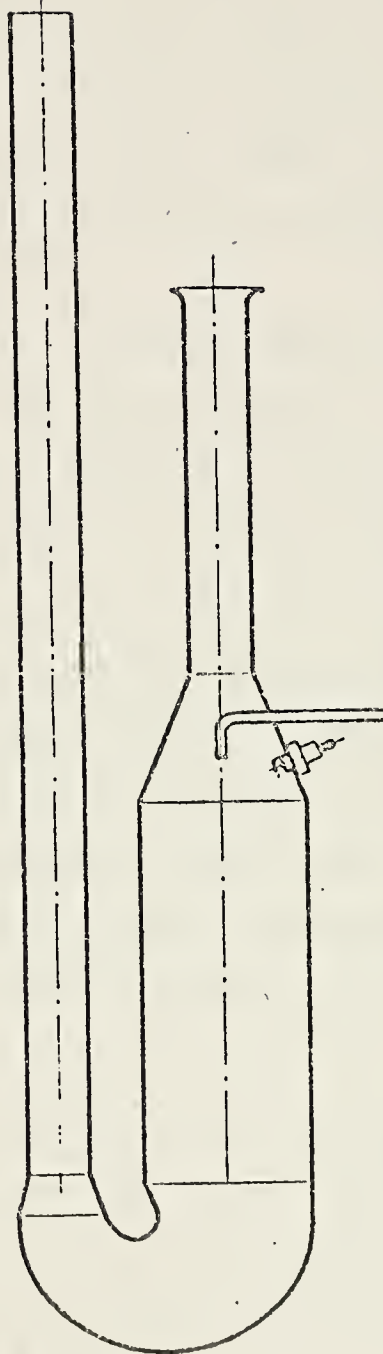


Figure 9. The configurations of BERTIN: a.) Escopette
b.) Ecrevisse (3)

With one particular device (fig. 10) a thrust of 147 lbs was obtained from a cluster of five (5) 5.25 in diameter pulsejets with augmentors. The SFC was 0.9 pph/lb. Thrust and thrust volume (thrust per unit volume of installation) was 120 lb/ft³. Lockwood felt that a thrust to weight ratio of 10 to 1 was possible with the then current state of the art, and actually achieved 12 to 1 with special sandwich construction.

Lockwood further concluded that the pulse reactor could be bent into a variety of shapes with little effect on performance if the internal surfaces remained reasonably smooth and the bends were not too sharp. All configurations studied were with valveless pulsejets and bending was therefore an important consideration since approximately 40% of the thrust was recovered from the bent intake. Multiple units were operated together in close proximity and the effect on performance was small with the configuration used.

Forward speed tests were conducted and engine performance showed continued improvement up to the maximum speed tested of 63 knots.

Lockwood believed that feasibility had been demonstrated in all critical areas, including starting, rapid control response, throttling from 25% to full throttle, durability (for lift engine applications), and maintenance of thrust level to at least 63 knots forward speed.

Lockwood [6] also conducted a considerable amount of research with several miniature, valveless pulsejet

configurations. The best of these configurations were tested singly and in clusters and the results are listed in Table I. Lockwood concluded from this study that such miniature pulsejets were suitable for thrust production and heater-blower applications.

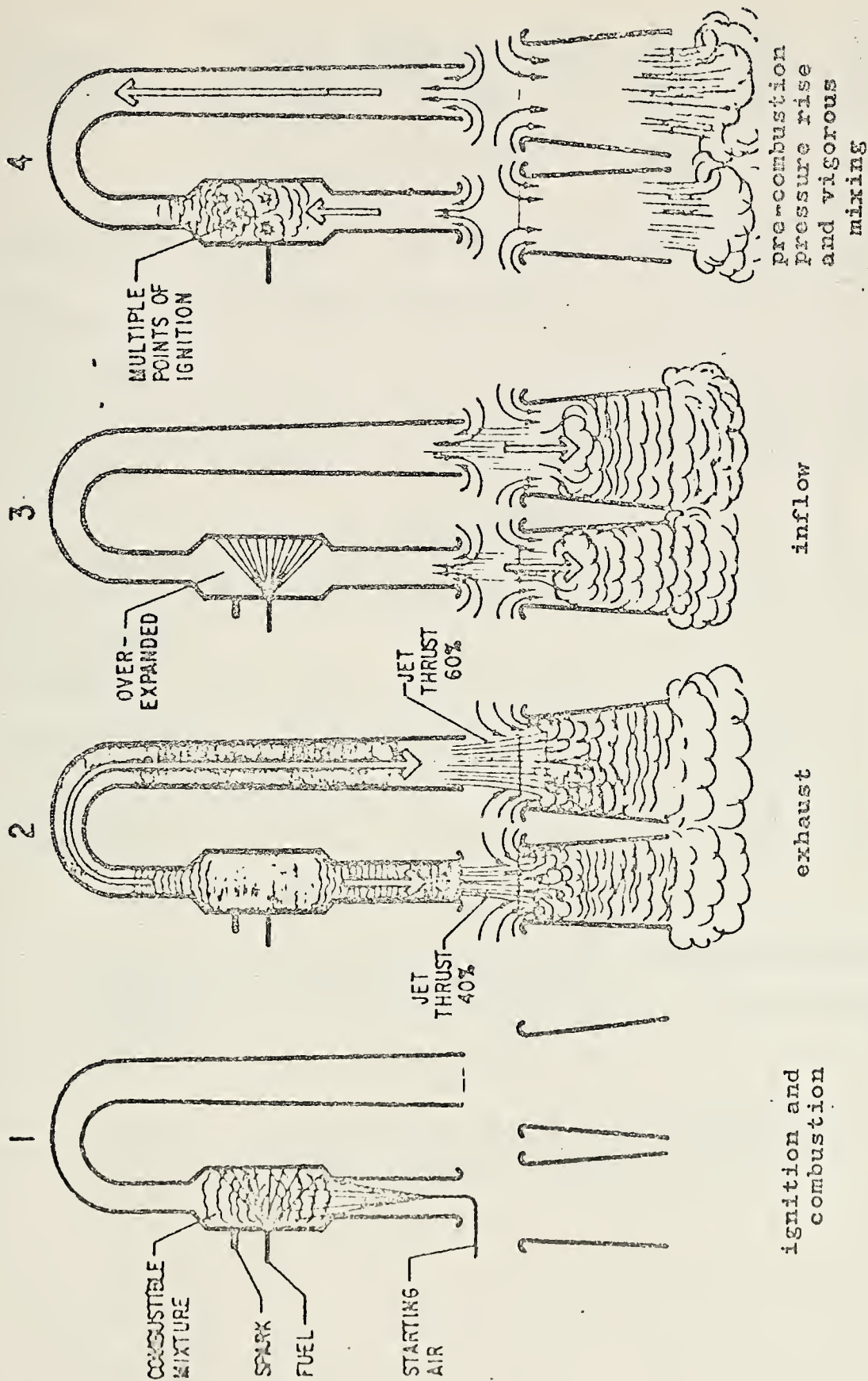


Figure 10. Operating cycle of LOCKWOOD's lift engine. (5)

VALVELESS PULSEJETS Designation	COMBUSTOR		TOTAL	1 Tsfc	FUEL	AUGMEN- TATION RATIO	TOTAL	1 Tsfc	FUEL
	Total	THRUST	min.	FLOW	THRUST		min.	FLOW	
	Dia.	Length	pounds	lb	RATE		max.,	lb	RATE
	max.	inches		hr·lb	pph		pounds	hr·lb	pph
SINGLE ENGINES									
	COMBUSTOR ONLY					AUGMENTED			
HC-1 (straight)	2.40	26.87	2.6	5.8	15.9	1.8	4.6	3.3	15.2
HC-1 4 (U-shaped)	(with modified fuel system)								
	2.40	26.87	2.2	5.2	10.7	-	-	-	-
HH-M1 (straight)	2.75	46.25	10.0	3.2	32.0	1.9	17.0	1.8	31.2
HH-M2 (straight)	3.25	51.13	12.5	3.4	42.5	1.8	23.0	1.9	13.7
MULTIPLE ENGINES									
HC-1 straight 6-in-line	2.40	26.87	11.5	6.3	72	1.9	2 13.5	5.0	67.5
HC-1 straight 6 rectangular cluster	2.40	26.87	9.2	7.8	72	-	-	-	-
HH-M1 straight (3-in-line)	2.75	46.25	23.0	3.3	76	1.8	2 36.0	1.9	68.5
HH-M2 straight (3-in-line)	3.25	51.13	31.0	3.4	103	1.6	2 47.5	2.2	102

- 1 Minimum Tsfc is usually near, but not at, fuel flow rate for maximum thrust (see referenced figures and text).
- 2 Total thrust was not maximum available due to fuel system supply limitation.
- 3 Accuracy of test data approximately $\pm 5\%$.

TABLE 1. Results of experiments by Lockwood with several pulsejet configurations [6].

IV. RECENT DEVELOPMENTS

A. INVESTIGATIONS BY ZHUBER-OKROG [3]

For at least thirty years there has been considerable uncertainty and controversy about the basic mechanism responsible for automatic ignition in a pulsejet and in 1966 Zhuber-Okrog began a research program to determine how a pulsejet achieved and maintained continuous automatic operation. For this investigation he used a 1/3 scale model of the original ARGUS Schmidt-tube (fig. 11).

The combustion chamber of this tube was water cooled so that automatic ignition of the mixture by the tube walls could be avoided. Ignition was provided by 14 spark plugs which could be synchronized and sequenced in varying ways by an electronic control system, details of which are included in Reference 7.

Automatic operation was observed at low fuel injection rates in a tube without flameholders and in this mode the spark plugs had no effect on the pulsations. However, as the fuel flow was increased, resulting in higher pressures, there was a point beyond which operation became erratic and the tube would not operate without spark ignition.

From these experiments, Zhuber-Okrog concluded that residual flames must be present during the intake phase in order to produce automatic ignition and continuous operation since he could rule out or control all other sources of ignition. As the pressure amplitude increased with increased

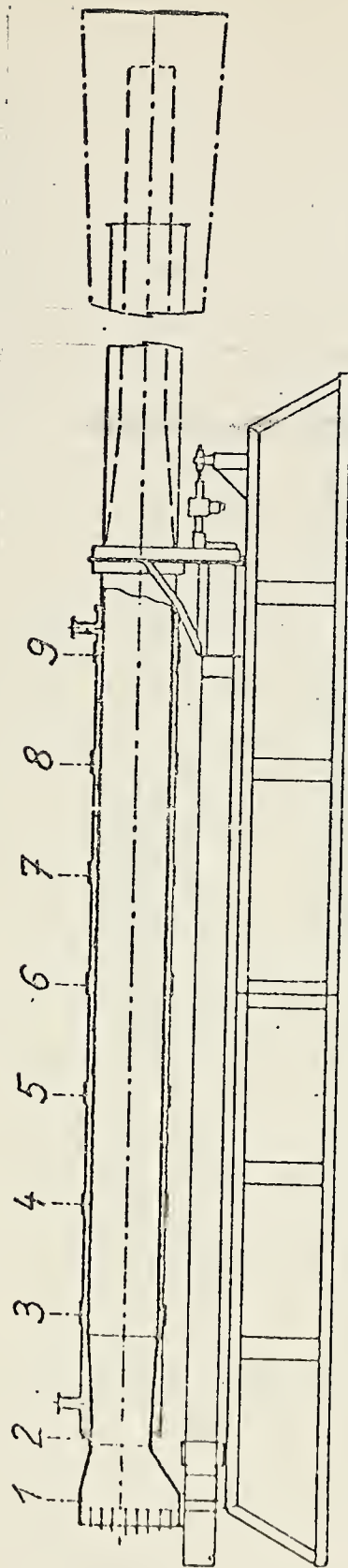


Figure 11a. The pulsejet used by ZHUBER-OKROG in his study of the ignition mechanism. (3)

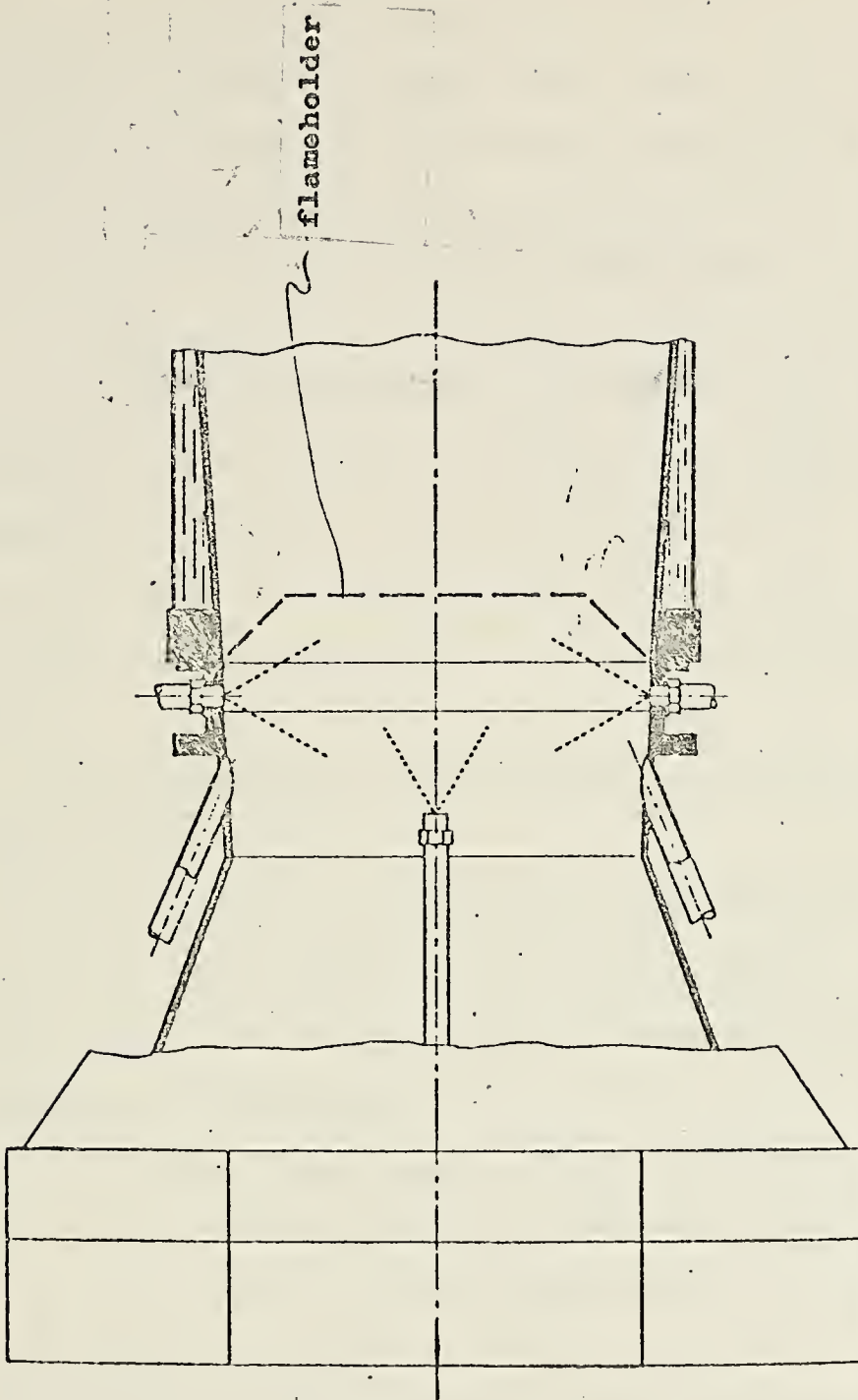


Figure 11b. Details of inlet section of ZHUBER-OKROG's pulsejet.
(3)

fuel flow, the inflow velocity increased, eventually exceeded the reaction velocity and flameout occurred because the flame could not propagate fast enough to support combustion throughout the chamber. From this it was concluded that flameholders of some sort were required, particularly at higher pressure amplitudes.

To substantiate this conclusion, Zhuber-Okrog installed a truncated cone flame-holder and observed that automatic operation could indeed be sustained with higher fuel/air ratios. A light sensor was placed ahead of the valves, and it can be seen in figures 12 and 13 that during automatic operation flames were present in the tube during the intake cycle.

The major points of Zhuber-Okrog's experiments can be summarized as follows:

a.) In order to retain suitable ignition flames during the intake cycle regions of low flow velocity are necessary. These regions can be provided by flameholders or step-changes in cross-section.

b.) These flameholders must be arranged so that the heat release during combustion increases with time.

c.) In order to achieve high pressure amplitudes, combustion should occur near the closed end of the tube, i.e. near the valves, and the chamber should be closed at one end to improve pressure buildup.

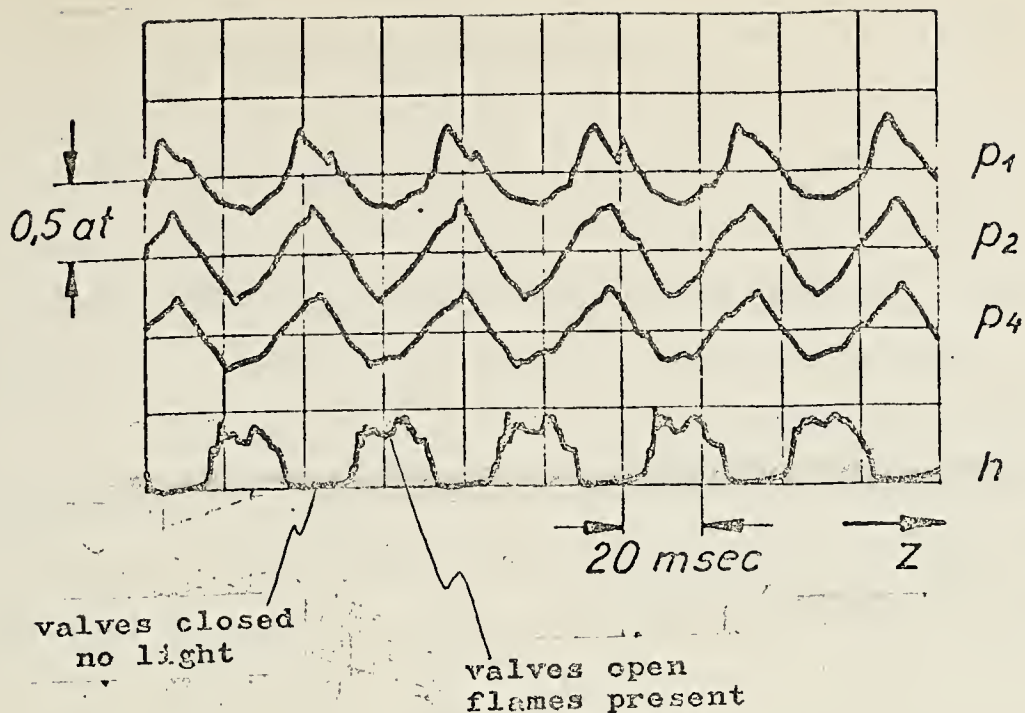


Figure 12. Pressure and flame indications in ZHUBER-OKROG's pulsejet. (3)

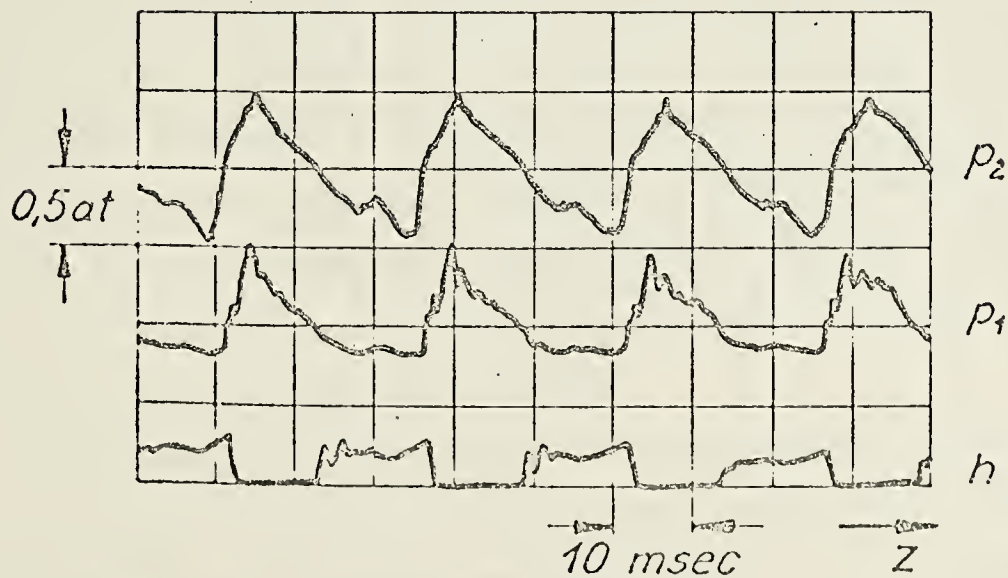


Figure 13. Pressure and flame indications in ZHUBER-OKROG's pulsejet under different operating conditions. (3)

d.) One end of the tube should be open to generate reflections of the compression and rarefaction waves essential for proper operation. Rarefaction waves cause reduced pressure and reflect as compression waves from the open end. These compression waves then bring the incoming mixture to virtually zero velocity to allow burning.

e.) In order to control inflow within proper limits a certain inflow resistance or backpressure is required.

f.) The tube length must be considerably longer than the tube diameter to ensure sufficient time for combustion.

B. INVESTIGATIONS BY MULLER [8]

J. L. Muller has recently conducted both experimental and theoretical work to determine the feasibility of applying pulsating combustion to gas turbines. In conventional gas turbine combustion chambers there is a pressure loss during the so called "constant pressure" combustion. Most of this loss is due to flameholders, turbulence, dilution of primary combustion products, and flame tube cooling. However, 20 to 30 percent of the overall combustion chamber pressure drop is due to the "fundamental heating loss" caused by a reduction in density and an increase in velocity when the combustion takes place at "constant" pressure.

Muller's theoretical work, to be examined in detail in Section V of this paper, predicts that rather than a pressure loss across the combustor, a pressure gain can be realized by utilizing pulsating combustion. Muller's analysis shows

that dilution air will be required in order to keep the temperature at an acceptable level, but that the introduction^{rt} of dilution air causes a substantial reduction in attainable combustion pressure ratios. When the pulse combustor is receiving air from a compressor, as in a gas turbine, larger quantities of dilution air are required as the compressor pressure ratio, and hence the delivery temperature, increase. This results in a substantial reduction in the combustor pressure ratio. This is shown in figures 14 and 15. These figures assume a fuel-air ratio of 0.05 and compressor and turbine efficiencies of 85%. However, even though the pressure gain in a pulsating combustion chamber is reduced by the introduction of dilution air, a worthwhile improvement in thermal efficiency may still be possible since there is a pressure loss in a conventional combustion chamber. If this loss is taken as 5 percent, a maximum theoretical improvment in thermal efficiency of about 16% is possible with moderate compressor pressure ratios and turbine inlet temperatures. This has the possibility of lowering fuel consumption by approximately 14% for the same power output [8]. However, these results have not yet been substantiated by experimental evidence.

Muller backed up his theoretical study with experimental work conducted with clustered pulsating combustion tubes with a common rotary inlet valve. This system was chosen because it appeared to be a feasible way of designing a

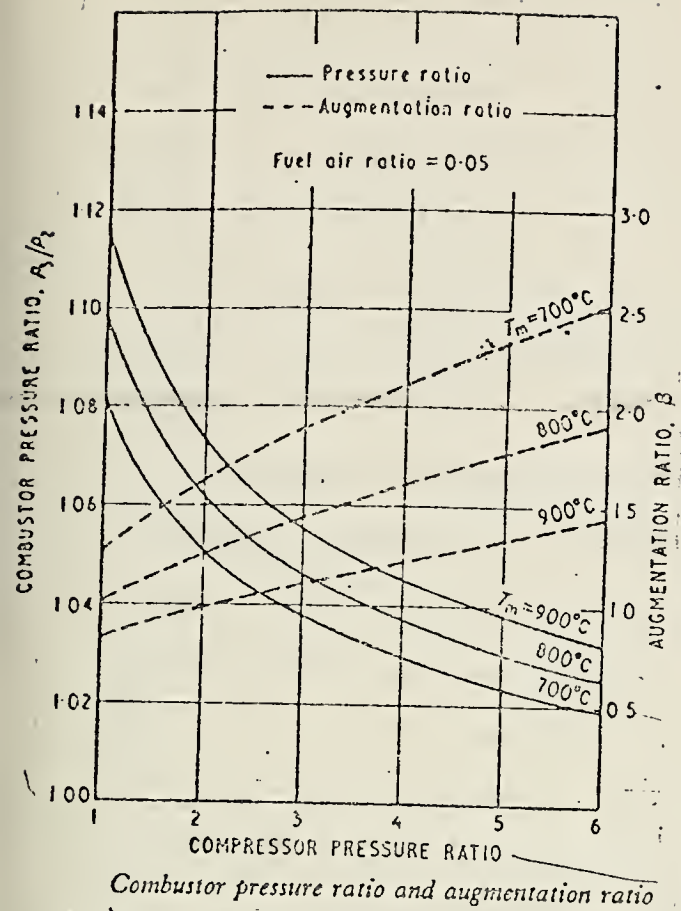
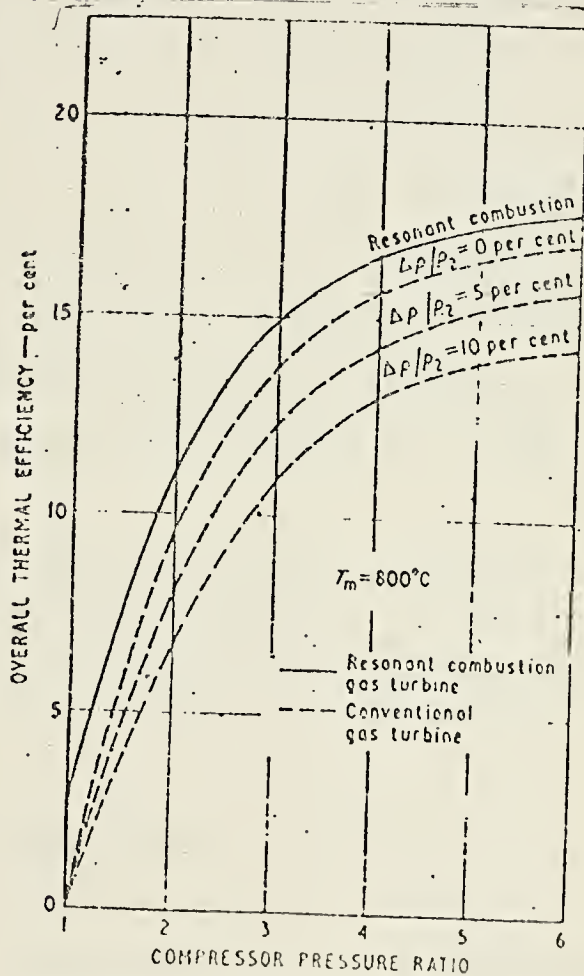


Fig. 14. Compressor pressure ratio versus combustor pressure ratio for a pressure gain gas turbine combustor. (8)

Fig. 15. Overall thermal efficiency versus compressor pressure ratio for a pressure gain gas turbine combustor. (8)



Comparison of theoretical overall gas turbine thermal efficiencies

compact resonant combustion system which would allow accurate phasing of the combustors in order to prevent undesirable pressure oscillations in the compressor and turbine, provide adequate valve life, and eliminate the complicated ducting of a valveless combustor [fig. 16).

The timing of Muller's combustion cycle was controlled mechanically rather than by gas dynamic considerations alone.

Muller's equipment provided for tangential flow of the inlet air into the combustion chamber and each combustion chamber was enclosed in a dilution duct. A performance gain was realized by interspacing an equal number of dilution ducts with those carrying the combustors in order to augment dilution air without heating it unnecessarily. The dilution air and combustion products were mixed in the pumping chamber and then flowed through augmentor tubes into the exhaust manifold. Back pressure was controlled by means of a valve in the exhaust duct.

The experiments were conducted with an inlet pressure of one (1) atmosphere. The operational frequency was very close to the Helmholtz resonant frequency rather than the quarter wave frequency.

The results from Muller's experiments showed that the test apparatus used, specific fuel consumption, combustor pressure ratio, and combustor efficiency were not particularly good, but that there was a pressure gain across the combustor.

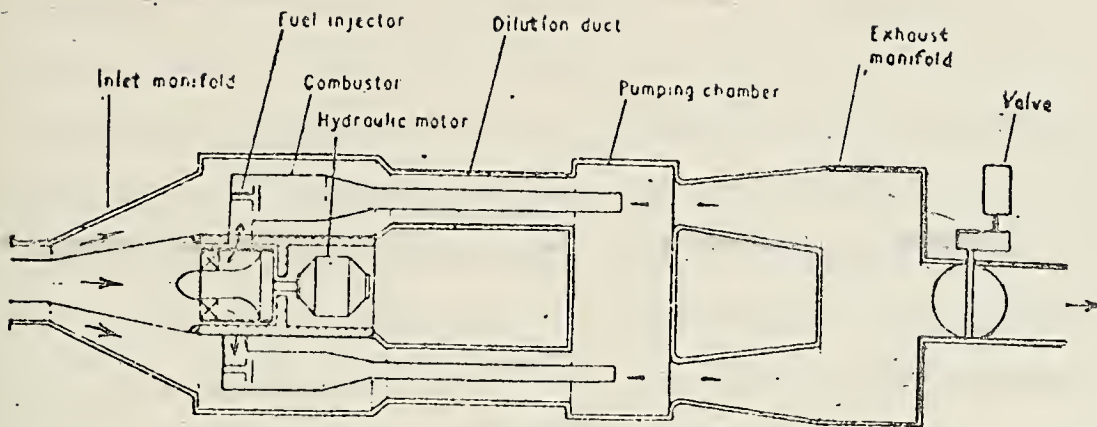


Figure 16. The pressure gain combustor of MULLER. (8)

Pressure amplitudes in the exhaust manifold varied by 2% and in the inlet duct by 4%.

Muller expresses little doubt that the combustors employed during his experiments could be improved. He feels that further development could result in considerably better performance than that assumed in the theoretical analysis and achieved during the experiments. He further states that the improvements in gas turbine performance with pulsating combustion depend mainly on the combustor design, pressure loss in the currently used combustor, and compressor outlet and turbine inlet temperature. As the compressor discharge temperature is increased the pressure gain in the combustor is somewhat decreased, but this effect can be offset by similar increases in the turbine inlet temperature.

Muller concludes that pressure gain combustion by means of pulsating combustion chambers is "feasible and practical" and that further development should be conducted.

C. RECENT WORK BY DORNIER AIRCRAFT COMPANY

Re-evaluation of the usefulness of the V-1 engine as a low cost propulsion device has recently been undertaken by the Dornier Aircraft Company in Germany. George Heise, in a paper published in the German "Journal for Aeronautical Sciences" [9] describes tests on a modified V-1 engine.

The unmodified V-1 engine had an upper speed limit of about 300 to 500 miles per hour. At these speeds the dynamic

pressure acting against the valves became so great that it interfered with their operation. As the engine encountered higher flight speeds the valves remained open for a longer portion of the cycle and this led to a condition in which the combustion phase required too large a portion of the cycle time. Initially, thrust increased slightly, but it then dropped off rapidly, depending on inflow resistance and tube geometry, and eventually flameout occurred.

There are two readily apparent solutions to this speed limitation; increase the valves' resistance to inflow as the flight speed increases or increase back pressure.

Increasing the flow resistance was suggested for the V-1 engine. Unfortunately, this increase in flow resistance was accompanied by a thrust decrease. However, an increase in back pressure proportionate to the ram pressure causes an increase in thrust with flight Mach number. Such a back pressure can be achieved by inserting an expanded section in the exhaust nozzle as shown in figure 17. The expanded section then provides for a buildup of back pressure but in some configurations will increase frontal area and hence aerodynamic drag.

Tests were conducted at speeds up to Mach 1.5 on a test stand of the DFVLR (German equivalent of NASA) in Trauen near Braunschweig, Germany. The results shows a parabolic increase of thrust with Mach number as shown in figure 18.

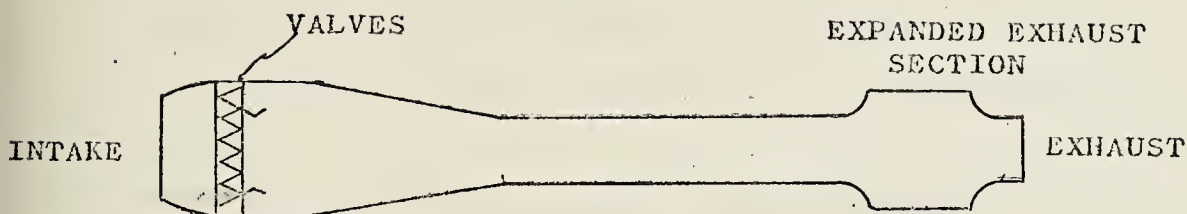


Figure 17. The modified V-1 engine of DORNIER.

Fig 11 T-5

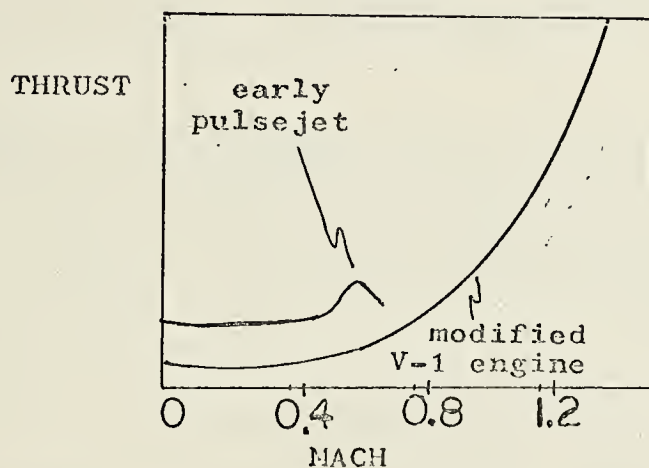


Figure 18. Thrust versus mach number for the modified V-1 engine tested by Dornier. (9)

D. WORK AT MESSERSCHMITT

In 1968 work was started in Germany by the Messerschmitt-Boelkow-Blohm GMBH on the development of a pulsejet engine for auxiliary power generation at supersonic and subsonic speeds. The basic configuration was essentially the valveless pulsejet of Bertin mentioned in Section 3 of this report.

A rather detailed design study was carried out including a thermodynamic analysis, a study of the non-steady flow processes, and the construction and testing of a prototype [10]. The basic configuration was modified by the addition of a supersonic inlet diffuser and by bending the exhaust tubes in such a way that the exhaust gases could drive a centrifugal turbine. This configuration is shown in figure 19.

Tests were conducted to measure pressures, temperatures, thrust, fuel consumption, and other operating parameters. Available power output was typically in the range of 100 to 250 shaft horsepower.

General conclusions arising from this work were that the pulsejet could be developed into a rugged, low cost auxiliary power unit, requiring little maintenance and capable of operation in the subsonic and supersonic ranges [10]. However, noise and vibration still are considerable disadvantages.

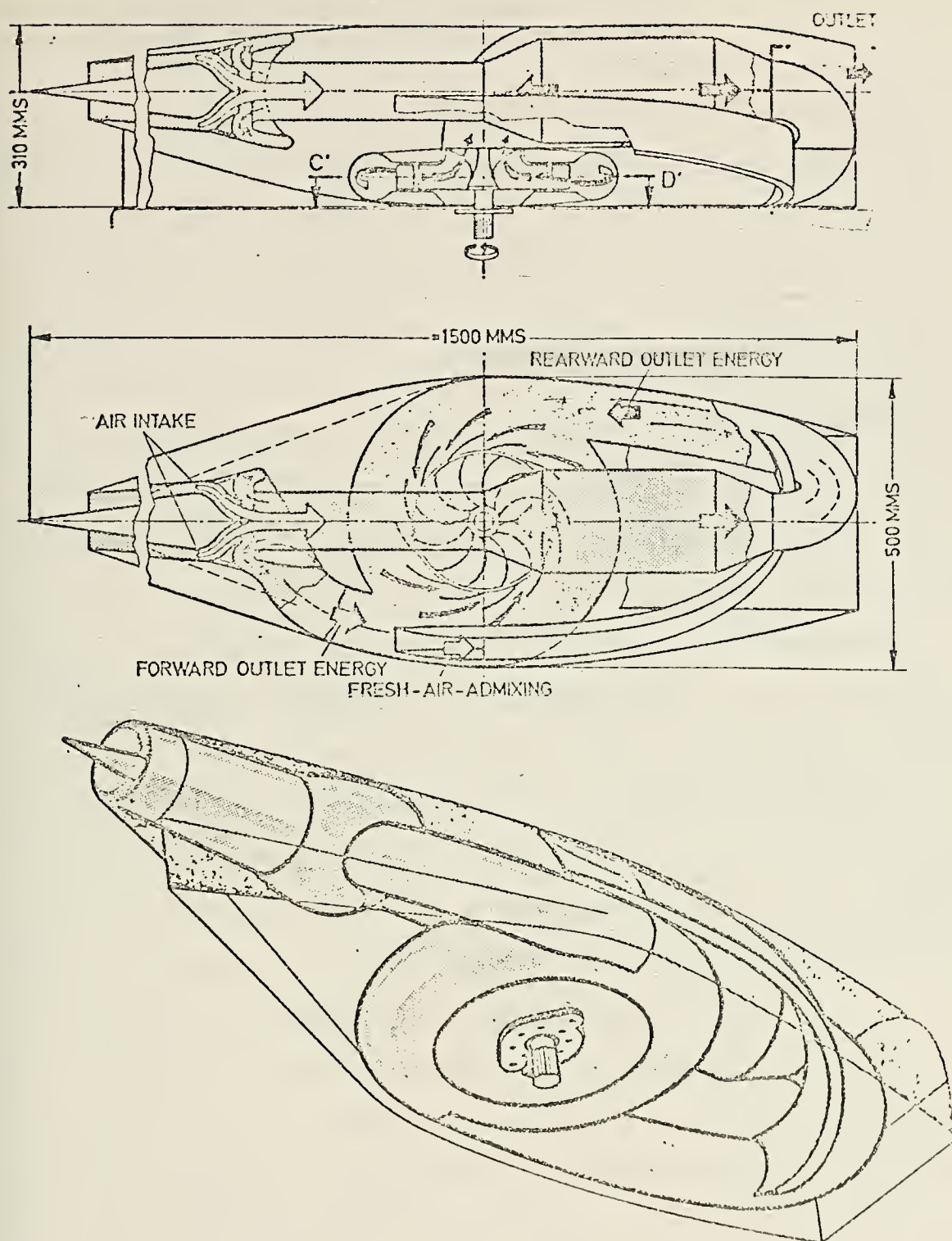


Figure 19. The auxiliary power unit of MESSERSCHMITT.
(10)

E. DESIGN AND TESTING OF HARMONIC BURNERS
FOR LOW POWER GAS TURBINES - THE WORK
OF SERVANTY

By looking at the efficiency of gas turbine components from an "available enthalpy" basis (available enthalpy is defined as the work required to return the fluid, reversibly, to ambient temperature and pressure). P. Servanty [11] showed that combustion chamber losses in conventional gas turbines could be as high as 38% even though there was no combustion pressure drop. The implication is that conventional methods of accounting for combustion chamber losses, the ratio of enthalpy produced to the enthalpy which would be produced if all available fuel were burned, is inadequate from an energetic efficiency standpoint, although still important for assessment of unburned fuel.

By looking at the combustion chamber efficiency in the way recommended by Servanty it is possible to identify a major source of losses in a gas turbine, and in particular, for gas turbines with low compression ratios. It is therefore possible to greatly improve gas turbine efficiency by reducing the losses in the combustion chamber.

Tests were conducted with single harmonic burners, clusters of five, and clusters of ten. A typical harmonic burner is shown in figure 20. A deterioration in performance was experienced when the units were clustered and three reasons were given for this:

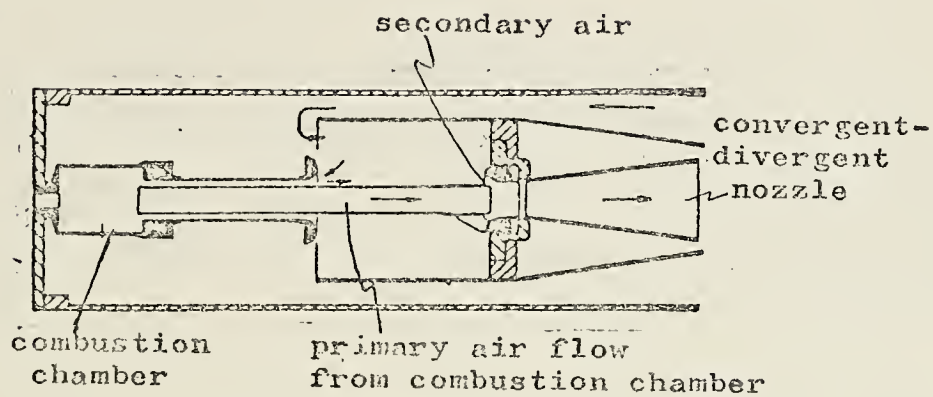


Figure 20. A harmonic combustion chamber of the type used in experiments by SERVANTY. (11)

1. Burner air feed path was less direct in clustered units.
2. Cross sectional area of the burner housing shroud had been reduced 60% in clustered units.
3. The fuel was changed from a liquid to a gaseous type and, therefore, positioning of the fuel nozzle may not have been optimum in the clustered designs.

Simultaneous ignition of a large number of harmonic burners also presented difficulties.

Major conclusions can be summarized as follows:

1. The pressure drop in a combustion chamber of a gas turbine with low compression ratio can be reduced by the use of pulsating harmonic combustors and perhaps a pressure gain is possible.

2. It appears difficult to make a high air-flow rate pulsating burner, without moving parts, of small enough size to be compatible with a gas turbine.

3. The optimum cluster consists of 4 or 5 individual pulsating burners of medium size (approximately 4 inch diameter). This places an upper limit of about 800 horsepower on gas turbines using such a clustered pulsating combustor.

F. THE WORK OF KENTFIELD

J. A. C. Kentfield has conducted theoretical and experimental work to establish the potential of pressure gain combustion, particularly for gas turbines. By a simple theoretical analysis he concluded that even a modest pressure gain in combustion appeared worthwhile for most gas turbines and that the fundamental performance limitations of constant volume combustion provided adequate room for development of

a practical pressure gain combustor [12]. Further, Cronje has shown that even pressure fluctuations as large as 10% have little effect on overall turbine efficiency [13].

The experimental program was in three parts. The object of the first part was to develop a simple pulsed combustor with one inlet and one outlet as shown in figure 21. The second part was conducted to provide a basis for developing a technically satisfactory ducted combustor of the type shown in figure 22. The third objective was to develop a short, simple inlet, ducted combustor. Valveless units were investigated in order to eliminate the mechanical complexity of valves.

Experimental work with the single inlet combustor tended to confirm the findings of Lockwood [6] with regard to performance and configuration. One problem, which could be of major importance for gas turbine use, was that the combustors were too long and attempts to shorten them by multiple inlets met with limited success.

The performance of the ducted version was somewhat disappointing when compared to the unducted version. This was believed to be caused by an improperly sized duct.

Extrapolation by Kentfield from the experimental results indicated "...that a pressure gain of between 2 and 3% should be attainable..." [12].



Figure 21. KENTFIELD'S single inlet pulse combustor. (12)

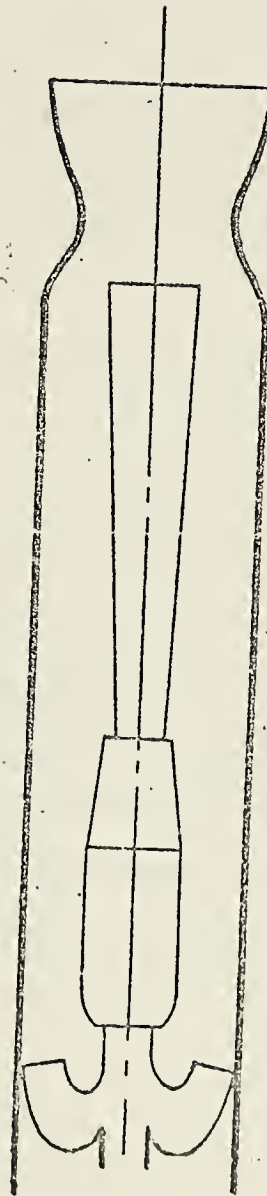


Figure 22. KENTFIELD'S improved ducted configuration. (12)

V. PULSEJET ANALYSIS

A. THERMODYNAMIC ANALYSIS

1. Ideal Combustion

In order to examine the pulsejet it is necessary to establish a reasonable thermodynamic model. Such a model is closely approximated by the processes occurring in one of the first internal-combustion engines, the Lenoir engine, and thus the Lenoir cycle can be applied to the basic pulsejet tube.

The Lenoir engine is a two-stroke piston engine without precompression. This engine takes in a stoichiometric fuel/air mixture during the first half of the downward piston stroke; halfway through the stroke the intake valve is closed and ignition occurs. The piston speed is at a maximum during ignition, but for our present discussion we will assume instantaneous combustion which is then a constant volume process. The combustion products expand during the second half of the stroke and produce mechanical power. The gases are exhausted during the upward stroke against a back pressure. The engine has no clearance volume and the back pressure does not impair the volumetric efficiency during the next intake stroke. Since the Lenoir engine takes in a fuel/air mixture at a low pressure and discharges the combustion products at a higher pressure, it can be used as a pressure generator. Proper timing of the spark will

make the pressure at the bottom of the power stroke equal to the back pressure to prevent throttling losses.

We now can see that the processes in a pulsejet tube are basically the same as in the Lenoir engine. These processes are shown in figure 23 and are

- 1.) Intake (0-1)
- 2.) Constant volume combustion (1-2)
- 3.) Isentropic expansion of combustion products (2-3)
- 4.) Exhaust at constant pressure (3-0')
- 5.) Valves open and a new cycle starts. (0-0')

We further assume that the Lenoir engine produces no mechanical work.

The following analysis is taken from Zhuber-Okrog [14].

The first law of thermodynamics applied to constant volume combustion process 1-2 gives

$$f(E_f + U_f) = U_2(1+f) - U_1 = C_v[T_2(1+f) - T_1] \quad (1)$$

where f = fuel/air ratio (stoichiometric for this case)

E_f = chemical energy of the fuel

U_f = internal energy of the fuel

C_v = constant volume specific heat between T_1 and T_2 .

Since

$$E_f + U_f = \text{heating value of the fuel} = Q_f = \text{constant}$$

we get

$$f Q_f = C_v[T_2(1+f) - T_1] \quad (2)$$

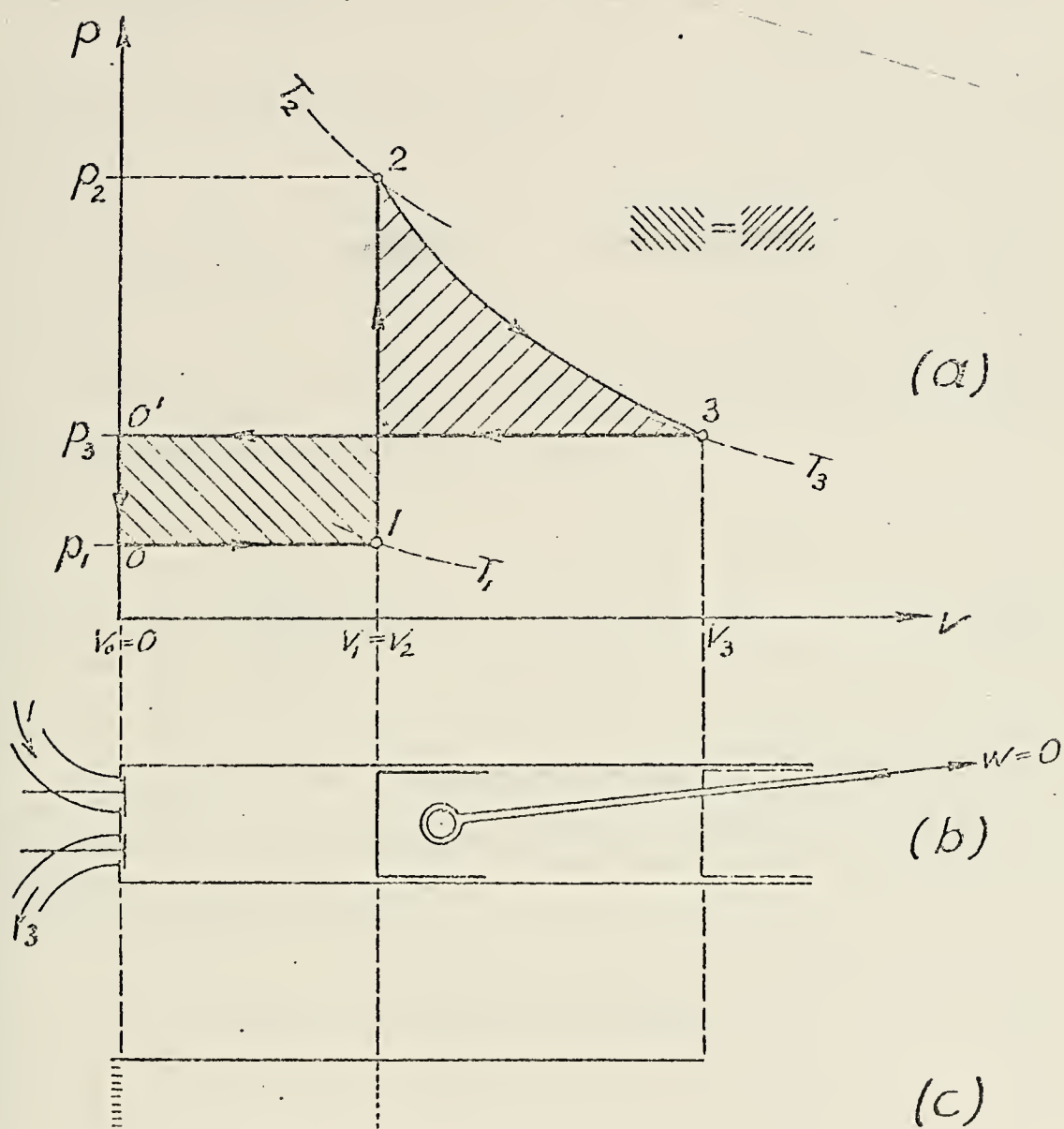


Figure 23. The ideal cycle (a) correlated with the Lenoir engine (b) and the simple combustion chamber (c). (14)

In any constant volume process,

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} = \Pi \quad (3)$$

Rewriting equation (2) we get

$$\frac{f Q_f}{C_v} + T_1 = T_2(1+f) \quad (4)$$

Combining equations (4) and (3) we develop an expression for temperature and pressure ratios, Π ,

$$\Pi = \frac{\frac{f Q_f}{T_1 C_v} + 1}{1+f} \quad (5)$$

Assuming the work output to be zero and recalling the relations for an isentropic process allows development of another useful relation

$$W = \int_2^3 P dv - (P_3 - P_1)V_3 - P_1(V_3 - V_1) = 0 \quad (6)$$

Since

$$\int_2^3 P dv = \frac{P_2 V_2 - P_3 V_3}{\gamma - 1} ,$$

we get

$$P_2 V_1 - P_3 V_3 - P_3 V_3 (\gamma - 1) + P_1 V_1 (\gamma - 1) = 0 \quad .$$

Dividing through by $P_1 V_1$

$$\frac{P_2 V_1}{P_1 V_1} - \frac{P_3 V_3}{P_1 V_1} - \frac{P_3 V_3}{P_1 V_1} (\gamma - 1) + (\gamma - 1) = 0$$

and remembering the ideal gas law

$$\frac{P_3 V_3}{P_1 V_1} = \frac{T_3}{T_1} \quad ,$$

and

$$\frac{P_2}{P_1} = \Pi \quad ,$$

yields

$$\Pi - \frac{T_3}{T_1} - \frac{T_3}{T_1} (\gamma - 1) + (\gamma - 1) = 0 \quad .$$

Rearranging

$$\frac{T_3}{T_1} = \frac{\Pi + (\gamma - 1)}{\gamma} \quad (7)$$

and substituting for Π from equation (5) results in

$$\frac{T_3}{T_1} = \frac{1}{(1+f)\gamma} \left[\frac{f_1 Q_f}{C_v T_1} - f \right] + 1 \quad . \quad (8)$$

This now establishes a relationship between the gases entering and leaving and the heating value of a particular fuel. Corresponding pressure and volume ratios can be derived from the isentropic relationships between states 2 and 3.

$$\begin{aligned}\frac{T_3}{T_1} &= \frac{P_3}{P_1} \frac{V_3}{V_1} = \frac{P_3}{P_1} \left(\frac{P_2}{P_3} \right)^{\frac{1}{\gamma}} && \text{since } P_2 = P_1 \\ &= \left(\frac{P_3}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \left(\frac{P_2}{P_1} \right)^{\frac{1}{\gamma}} = \left(\frac{P_3}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \Pi^{\frac{1}{\gamma}}.\end{aligned}$$

Therefore,

$$\frac{P_3}{P_1} = \frac{\left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{\gamma-1}}}{\Pi^{\frac{1}{\gamma-1}}} \quad (9)$$

Finally, from the perfect gas law we have

$$\frac{V_3}{V_1} = \frac{T_3 P_1}{T_1 P_3} \quad (10)$$

Values of γ , C_p , and C_v for varying temperatures of air and combustion products are shown in figures 24 and 25.

Figure 24. Specific heats, C_p and C_v , of air and combustion products of fuel and air (stoichiometric). (14)

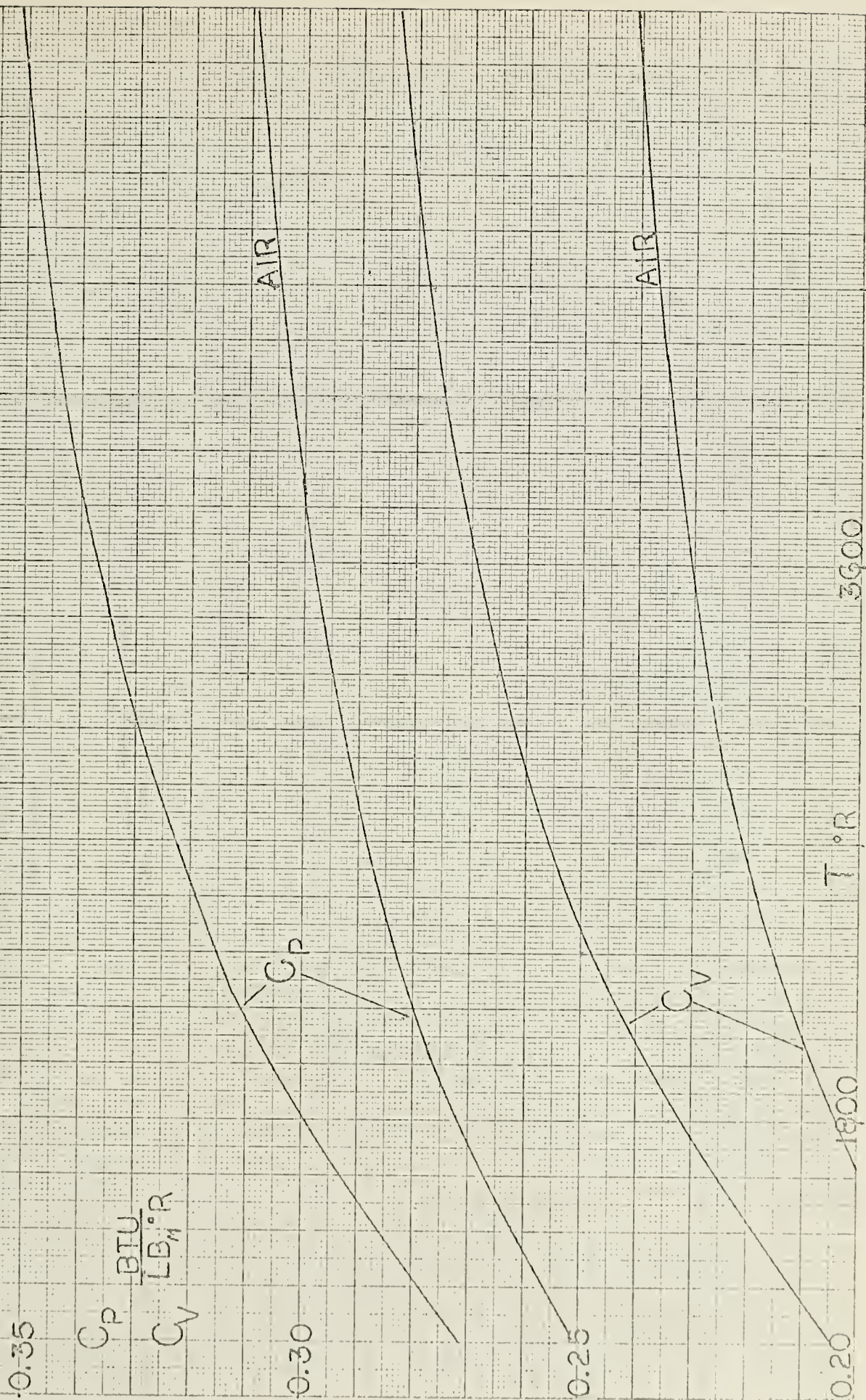
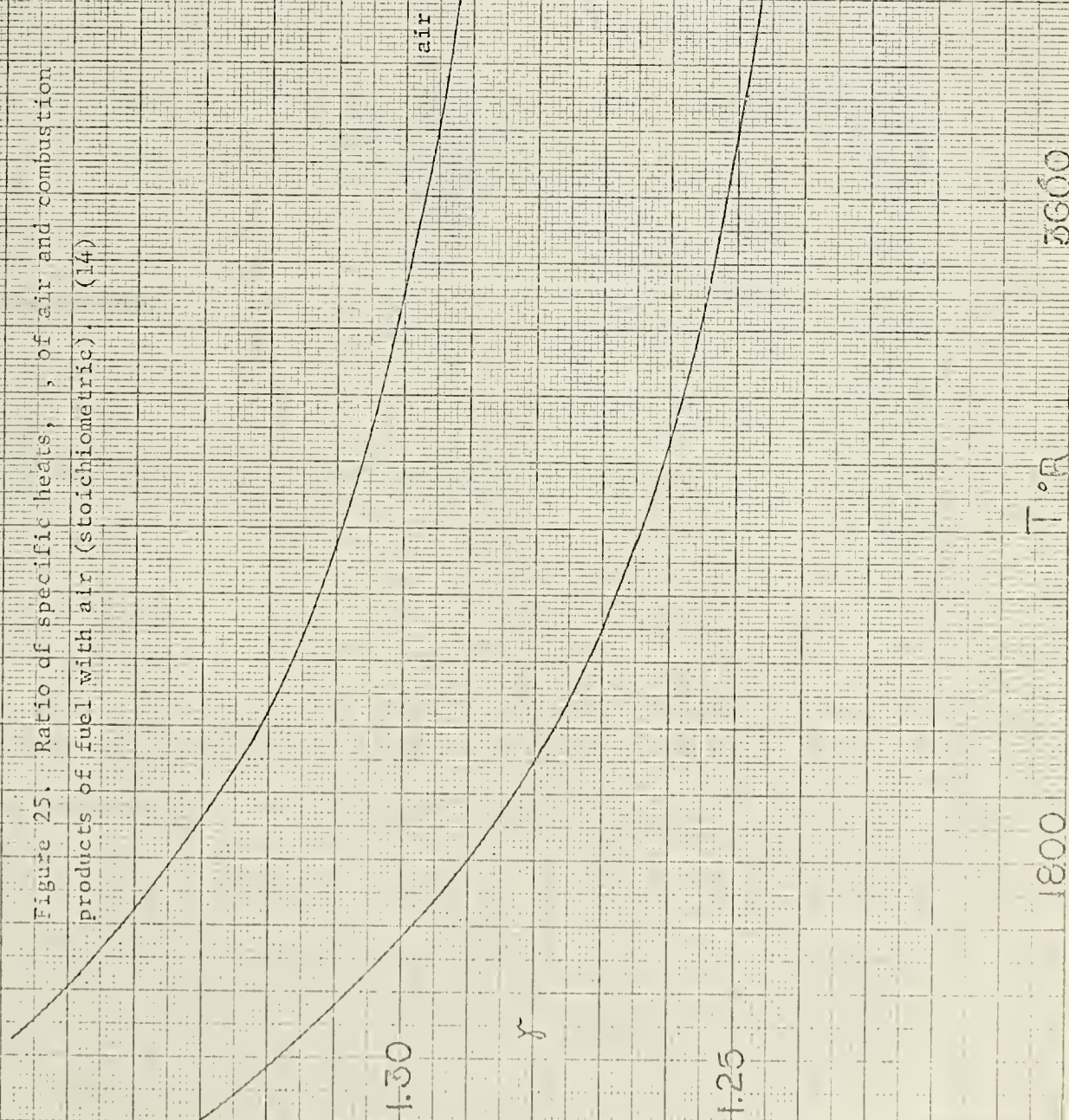


Figure 25. Ratio of specific heats, γ , of air and combustion products of fuel with air (stoichiometric). (14)



Example:

fuel - typical hydrocarbon

$$Q_f = 18,950 \text{ Btu/lbm}$$

$$f = 0.0667$$

$$\gamma = 1.243 \text{ (estimated average value for temperature range considered) [14]}$$

$$C_v = 0.257 \text{ Btu/lbm. (estimated average value for temperature range considered) [14]}$$

$$P_1 = 14.7 \text{ psi}$$

$$T_1 = 519^\circ\text{R}$$

$$\Pi = \frac{\frac{f Q_f}{T_1 C_v} + 1}{1 + f} = \frac{\frac{0.0667(18,950)}{519 \times 0.257} + 1}{1.0667}$$

$$\Pi = 9.817$$

$$\frac{T_3}{T_1} = \frac{\Pi + (\gamma - 1)}{\gamma} = \frac{9.817 + (1.243 - 1)}{1.243}$$

$$\frac{T_3}{T_1} = 8.09$$

$$T_3 = 8.09 \times 519^\circ\text{R}$$

$$T_3 = 4200^\circ\text{R}$$



$$\frac{P_3}{P_1} = \frac{\left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{\gamma-1}}}{\frac{1}{\gamma-1}} = \frac{\frac{1.243}{1.243-1}}{(8.09) \frac{1}{1.243-1}}$$

$$\frac{P_3}{P_1} = 3.6$$

$$\frac{V_3}{V_1} = \frac{T_3}{T_1} \frac{P_1}{P_3} = \frac{8.09}{3.6}$$

$$\frac{V_3}{V_1} = 2.25$$

Results of this analysis are shown in figure 26. It can be seen that there is a strong dependence on inlet temperature, T_1 , which could present difficulties when the combustion chamber receives air from a compressor with a high pressure ratio and the resulting high exit temperature. Worthy of note is the pressure ratio P_3/P_1 (from 2.0 to 3.5). This is, of course, an ideal process and should be viewed with caution, but a pressure gain of even 2 is a worthwhile incentive for further study.

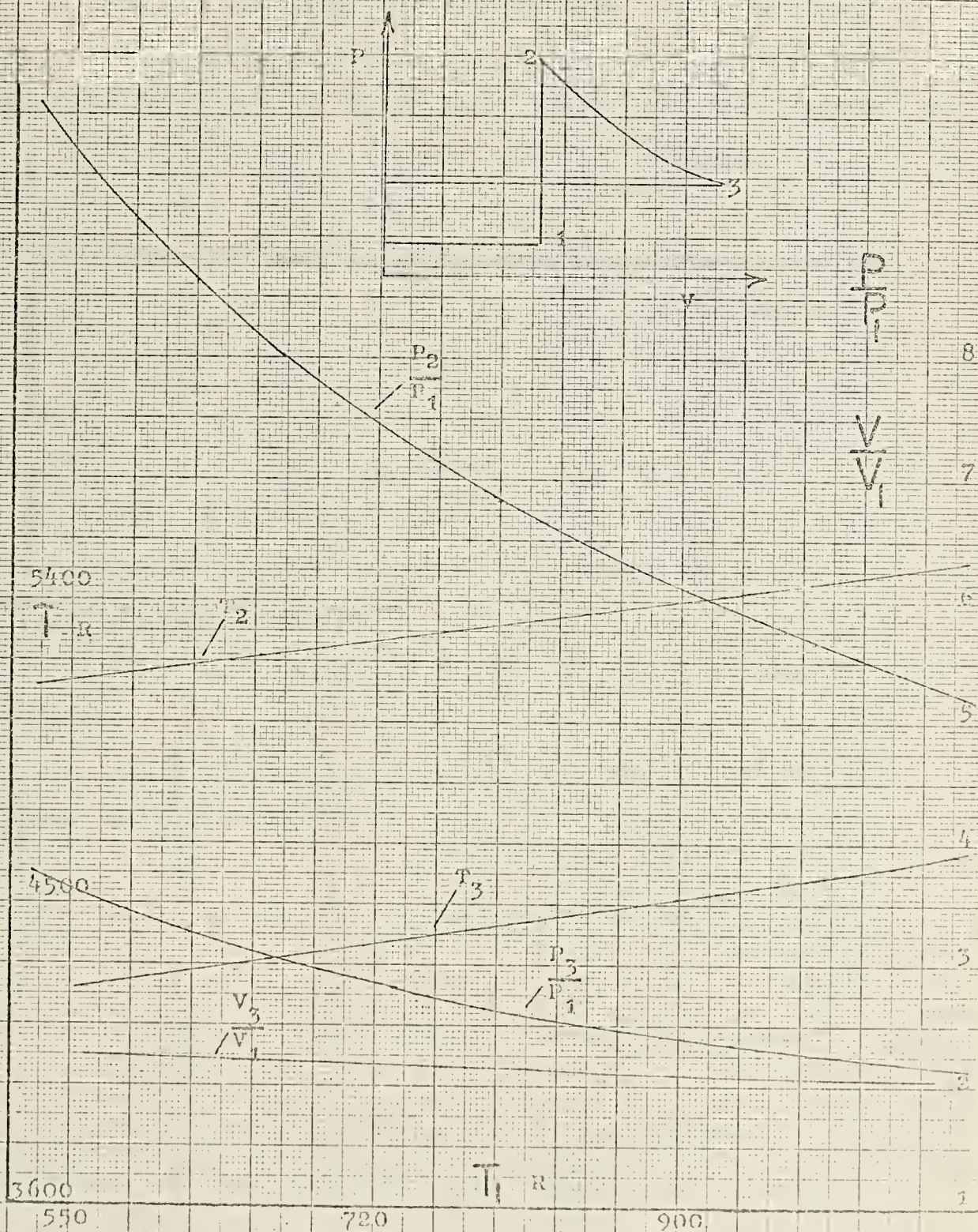


Figure 26. Values of temperature, pressure, and volume ratios achieved in an ideal Lenoir engine (using stoichiometric combustion) against inlet temperature, T_1 . (14)



2. Thermodynamic Analysis of a Pulsejet Tube With Finite Combustion Interval [14]

The previous analysis assumed that the combustion took place in an infinitely short period of time which is obviously not going to happen in an actual process. Therefore, it is necessary to examine a cycle in which the combustion occurs in a finite time span.

Again, the ideal Lenoir engine is used as a model for our analysis with the distinction being made that the combustion is no longer a constant volume process since burning is not instantaneous. The pressure volume diagram for this cycle is shown in figure 27. A linear relationship is assumed between points 1 and 2 both for simplicity and because that provides a reasonable approximation to the actual processes involved.

All other processes are the same as in the previous analysis.

The following relationships are established for the combustion process [3].

$$f Q_f - W_c = \overline{C}_v [T_2(1+f) - T_1] \quad (11)$$

where W_c = work done during combustion.

Rearranging and dividing through by T_1 results in an expression for the temperature ratio T_2/T_1

$$\frac{T_2}{T_1} = \frac{1}{1+f} \left[\frac{f Q_f}{\bar{C}_v T_1} - \frac{R}{\bar{C}_v} \frac{W_c}{R T_1} + 1 \right] \quad (12)$$

Establishing the work balance for unit mass gives

$$W = P_1 V_1 - P_3 V_3 + \int_1^2 P dv + \int_2^3 P dv = 0 \quad (13)$$

as before

$$\int_2^3 P dv = \frac{P_2 V_2 - P_3 V_3}{\gamma - 1} = \frac{R(T_2 - T_3)}{\gamma - 1}$$

for isentropic expansion, and noting that

$$\int_1^2 P dv = W_c$$

we get

$$P_1 V_1 - P_3 V_3 + W_c + \frac{R(T_2 - T_3)}{\gamma - 1} = 0$$

Applying the ideal gas law and rearranging gives an expression for the ratio T_3/T_1 .

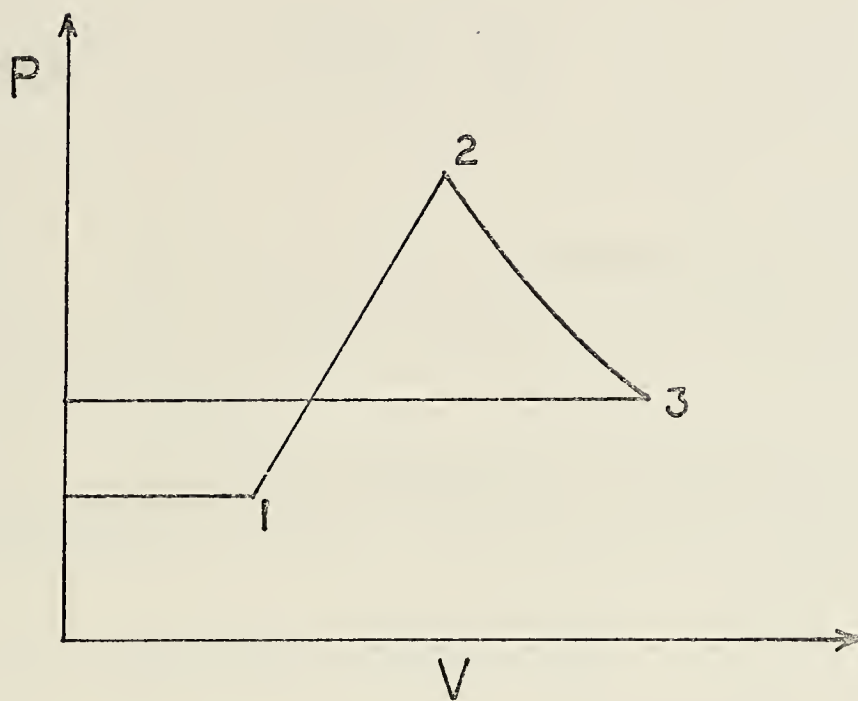


Figure 27. Pulsejet cycle with finite combustion.



$$R T_1 - R T_3 + W_c + \frac{R(T_2 - T_3)}{\gamma - 1} = 0$$

$$1 - \frac{T_3}{T_1} + \frac{W_c}{R T_1} + \frac{(T_2 - T_3)}{(\gamma - 1) T_1} = 0$$

$$(\gamma - 1) - (\gamma - 1) \frac{T_3}{T_1} + \frac{W_c}{R T_1} (\gamma - 1) + \frac{T_2}{T_1} - \frac{T_3}{T_1} = 0$$

$$\frac{T_3}{T_1} = \frac{1}{\gamma} \left[(\gamma - 1) \frac{(1 + W_c)}{R T_1} + \frac{T_2}{T_1} \right] \quad (14)$$

The ratio T_2/T_1 was determined previously, T_1 is known, and γ and R are constants, but an expression for W_c is now required.

It will be assumed that the variation of pressure with specific volume is linear and this yields;

$$W_c = \frac{1}{2} (P_1 + P_2)(V_2 - V_1) \quad (15)$$

applying the perfect gas law

$$W_c = \frac{P_1 + P_2}{2} \left(\frac{R T_2}{P_2} - \frac{R T_1}{P_1} \right)$$

$$W_c = \frac{R T_1}{2} \left[\frac{T_2}{T_1} \frac{P_1}{P_2} + \frac{T_2}{T_1} - \frac{P_2}{P_1} - 1 \right] \quad (16)$$

This can then be non-dimensionalized by simply dividing through by $R T_1$, and this yields

$$\frac{W_c}{R T_1} = \frac{1}{2} \left[\frac{T_2}{T_1} \frac{P_1}{P_2} + \frac{T_2}{T_1} - \frac{P_2}{P_1} - 1 \right] \quad (17)$$

which is required in equations (12) and (15).

The expression for W_c now required P_2/P_1 and these pressures can be easily measured in an experimental setup. To be handled analytically P_2/P_1 is assumed and T_2/T_1 is guessed. This yields $W_c/R T_1$ which is then used in equation 12 to verify the selection of T_2/T_1 .

The expression for P_3/P_1 , and V_3/V_1 can be obtained from the isentropic relations between states 2 and 3 and the ideal gas law.

$$\frac{P_3}{P_1} = \frac{P_2}{P_1} \frac{P_3}{P_2} = \frac{P_2}{P_1} \left[\frac{T_3}{T_1} \frac{T_1}{T_2} \right]^{\frac{\gamma}{\gamma-1}}$$

This expression emphasizes the importance of the pressure ratio P_2/P_1 .

The volume ratio V_3/V_1 then becomes:

$$\frac{V_3}{V_1} = \frac{T_3}{T_1} \frac{P_1}{P_3}$$

Once again, γ and \bar{C}_v are selected for an average temperature.

Numerical Example

$$Q_f = 18,950 \text{ Btu/lbm}$$

$$f = 0.0667$$

$$\gamma = 1.265$$

$$\bar{C}_v = 0.250 \text{ Btu/lbm } ^\circ\text{R}$$

$$P_1 = 14.7 \text{ psi}$$

$$T_1 = 59^\circ\text{F} \approx 519^\circ\text{R}$$

$$\text{Assume: } \frac{P_2}{P_1} = 6.0 \quad \frac{T_2}{T_1} = 9.0$$

$$\begin{aligned} \frac{W_c}{R T_1} &= \frac{1}{2} \left(\frac{T_2}{T_1} \frac{P_1}{P_2} + \frac{T_2}{T_1} - \frac{P_2}{P_1} - 1 \right) \\ &= \frac{1}{2} \left(\frac{9.0}{6.0} + 9.0 - 6.0 - 1 \right) = 1.75 \end{aligned}$$

$$\frac{T_2}{T_1} = \frac{1}{1+f} \left[\frac{Q_f f}{\bar{C}_v T_1} - \frac{R}{\bar{C}_v} \frac{W_c}{R T_1} + 1 \right]$$

$$0 \stackrel{?}{=} \frac{1}{1.0667} \left[\frac{18.950 \times 0.0667}{0.250 \times 519} - \frac{53.4}{0.250} \times \frac{1.75}{778} + 1 \right] - 9.0$$

$$0 \stackrel{?}{=} \frac{1}{1.0667} [10.737 - 0.274(1.75)] - 9.0$$

$$0 \stackrel{?}{=} 0.615 \quad \text{NO!}$$

$$\text{Assume: } \frac{P_2}{P_1} = 6.0 \quad \frac{T_2}{T_1} = 9.6$$

$$\frac{W_c}{R T_1} = \frac{1}{2} \left[\frac{9.6}{6} + 9.6 - 7 \right] = 2.1$$

$$0 \stackrel{?}{=} \frac{1}{1.0667} [10.737 - 0.274(2.1)] - 9.6$$

$$0 \stackrel{?}{=} 0.992 \quad \text{NO!}$$

$$\text{Assume: } \frac{P_2}{P_1} = 6.0 \quad \frac{T_2}{T_1} = 9.53$$

$$\frac{W_c}{R T_1} = \frac{1}{2} \left[\frac{9.52}{6} + 9.53 - 7 \right] = 2.059$$

$$0 \stackrel{?}{=} \frac{1}{1.0667} [10.737 - 0.274(2.059)] - 9.53$$

$$0 \stackrel{?}{=} 6.38 \times 10^{-3} \approx 0$$

$$\frac{T_2}{T_1} = 9.53 \quad \frac{P_2}{P_1} = 6.0 \quad \frac{W_c}{R T_1} = 2.059$$

$$\gamma = 1.265$$

$$\frac{T_3}{T_1} = \frac{1}{1.265} [(1.265 - 1)(1 + 2.059) + 9.53] = 8.174$$

$$T_3 = 8.174 \times 519$$

$$T_3 = 4242^\circ\text{R}$$

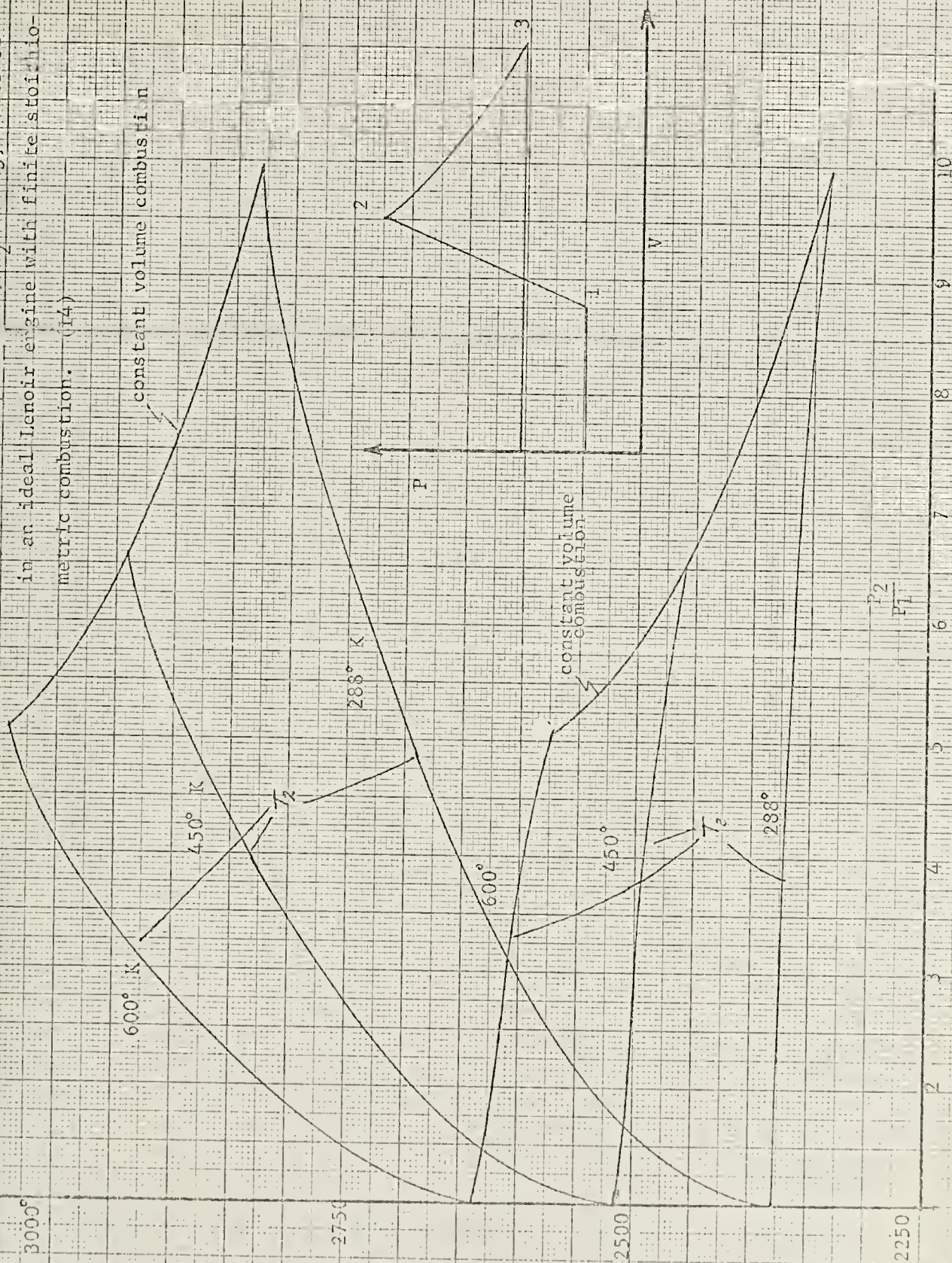
Results of this analysis are shown in figures 28 and 29. Slight deviations from ideal constant volume combustion have relatively little effect on the Lenoir cycle, and even though combustion is finite there is theoretically an appreciable pressure rise. If, however, the process varies more than just slightly from constant volume combustion, the effects on overall performance can be significant. Strong dependence on the peak pressure attained is shown in figure 29.

3. Thermodynamic Analysis of a Pulsating Gas Turbine Combustor by F. H. Reynst [2]

Reynst believed that investigation of pulsating combustion phenomena could eventually lead to many feasible applications including use in gas turbine combustion chambers. The constant volume process of ideal pulsating combustion does have higher thermal efficiency than a constant pressure cycle of the same heat input. In this analysis, Reynst demonstrated how much improvement could be achieved in a gas turbine using pulsating combustion compared to the same machine using constant pressure combustion. Then analysis of a third cycle, in which cooling air is raised to the same pressure as the hot gases from the pulsating combustor shows that in this way even greater efficiencies are possible than with the use of pulsating combustion alone.

Reynst begins by establishing a heat balance for constant volume and constant pressure combustion assuming that the heat input is equal in each case.

Figure 28. Temperatures, T_2 and T_3 , achieved in an ideal Lenoir engine with finite stoichiometric combustion. (i4)



Pressure-volume and temperature-entropy diagrams for these cycles are shown in figures 30 and 31.

$$C_P(T_3 - T_2) = C_V(T_7 - T_2) \quad (18)$$

Noting that $C_P = \gamma C_V$, and that $T_3 = T_5$ leads to

$$\gamma C_V(T_5 - T_2) = C_V(T_7 - T_2) \quad .$$

Defining $\Pi = \frac{P_7}{P_2} = \frac{T_7}{T_2}$, which is true for constant volume combustion;

$$\gamma(T_5 - T_2) = \Pi T_2 - T_2$$

$$\Pi = \frac{\gamma T_5}{T_2} - \gamma + 1 \quad (19)$$

Thus a relation between the compressor exit pressure and the peak pressure occurring during combustion is established.

From the isentropic relationships we have for expansion:

$$\begin{aligned} \frac{P_5}{P_7} &= \left(\frac{T_5}{T_7} \right)^{\frac{\gamma}{\gamma-1}} \\ P_5 &= P_7 \frac{P_2}{P_2} \left(\frac{T_5}{T_7} \frac{T_2}{T_2} \right)^{\frac{\gamma}{\gamma-1}} \\ P_5 &= \Pi P_2 \left(\frac{T_5}{T_2} \frac{1}{\Pi} \right)^{\frac{\gamma}{\gamma-1}} \\ P_5 &= \Pi P_2 \left(\frac{\Pi + \gamma - 1}{\Pi \gamma} \right)^{\frac{\gamma}{\gamma-1}} \end{aligned} \quad (20)$$

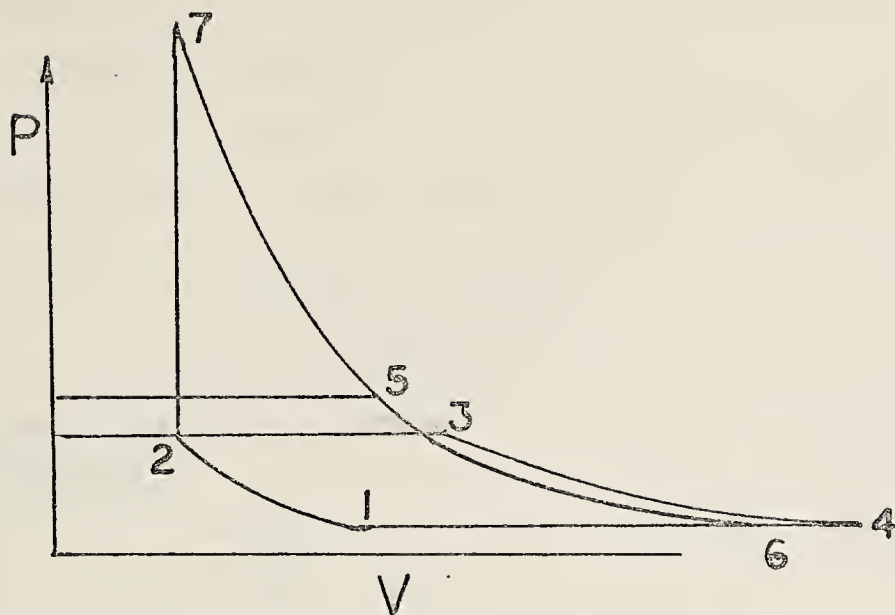


Figure 30. Pressure-Volume diagram for gas turbine pulse combustor with ideal combustion.

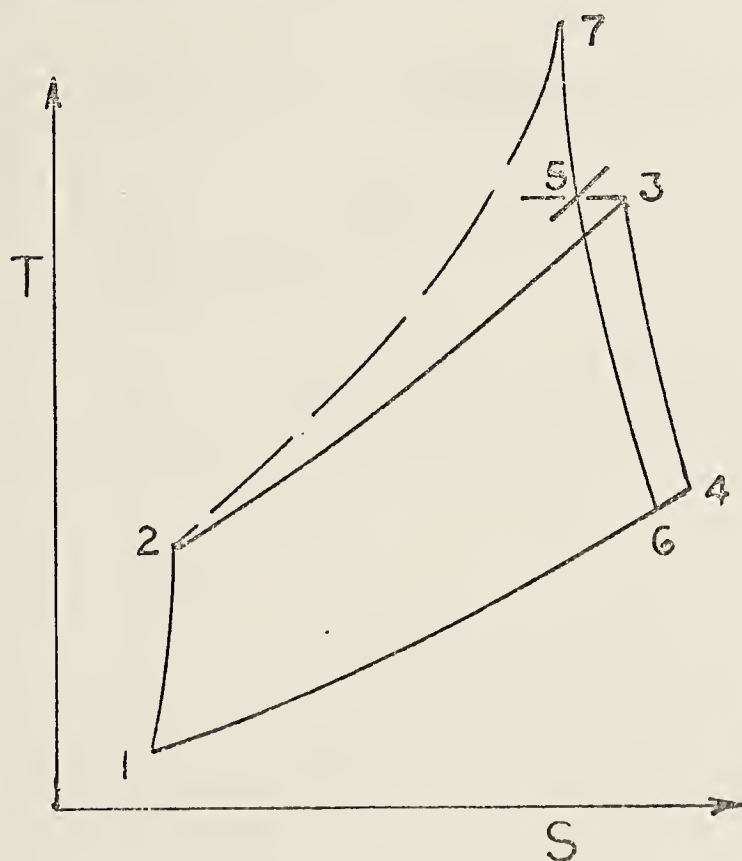


Figure 31. Temperature-Entropy diagram for gas turbine pulse combustor with ideal combustion.

Equation (20) is an expression for the pressure after the pulsating combustor.

In order to calculate the thermal efficiency of the constant pressure gas turbine we will use the formula [2]:

$$\eta = \frac{(T_3 - T_4) - (T_2 - T_1)}{(T_3 - T_2)}$$

Example:

$$\gamma = 1.4$$

$$T_1 = 59^\circ\text{F} = 519^\circ\text{R}$$

$$T_3 = 2000^\circ\text{F} = 2460^\circ\text{R} \quad (\text{assumed turbine inlet temperature})$$

Compressor and turbine efficiencies of 90%

$$\frac{P_2}{P_1} = 6 \quad \text{Compressor ratio}$$

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 519(6)^{\frac{1.4-1}{1.4}}$$

$$T_{2s} = 866^\circ\text{R}$$

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$T_2 = \frac{T_{2s} - T_1}{0.9} + T_1 = \frac{866 - 519}{0.9} + 519$$

$$T_2 = 904^\circ\text{R}$$

Assuming no pressure loss in the combustor and full expansion in the turbine

$$\frac{P_3}{P_4} = 6$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = (6)^{\frac{0.4}{1.4}}$$

$$\frac{T_3}{T_4} = 1.6685$$

$$\eta_t = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

$$T_4 = T_3 - \eta_t (T_3 - T_{4s})$$

$$T_4 = 2460 - 0.9(2460 - 1474)$$

$$T_4 = 1572^\circ\text{R}$$

$$\eta_{C_P} = \frac{(2460 - 1572) - (904 - 519)}{(2460 - 904)} \times 100$$

$$\eta_{C_P} = 32.3\%$$

Now the constant-pressure combustion chamber is replaced by a pulsating combustion chamber and the efficiency recalculated.

$$\Pi = 1.4 \left(\frac{2460}{904} \right) - 1.4 + 1$$

$$\Pi = 3.41$$

$$P_5 = 3.41 P_2 \left(\frac{3.41 + 1.4 - 1}{3.41 \times 1.4} \right)^{\frac{1.4}{0.4}} = 1.55 P_2$$

$$\frac{P_5}{P_2} = 1.55$$

This is the theoretical pressure ratio across the pulsating combustor.

$$\frac{P_5}{P_2} \frac{P_2}{P_1} = 1.55(6)$$

$$\frac{P_5}{P_1} = 9.3 \quad \text{and} \quad P_6 = P_1$$

$$\frac{P_5}{P_6} = 9.3$$

$$\frac{T_5}{T_{6s}} = \left(\frac{P_5}{P_6} \right)^{\frac{\gamma-1}{\gamma}} = (9.3)^{\frac{0.4}{1.4}} = 1.891$$

$$T_{6s} = \frac{T_5}{1.891} = \frac{T_3}{1.891} = \frac{2460}{1.891}$$

$$T_{6s} = 1300^\circ\text{R}$$

$$T_6 = T_5 - \eta_t (T_5 - T_{6s}) = 2460 - 0.9(2460 - 1300)$$

$$T_6 = 1416^\circ\text{R}$$

The thermal efficiency for constant pressure combustion is given by

$$\begin{aligned}\eta_{C_v} &= 100 \times \frac{(T_5 - T_6) - (T_2 - T_1)}{(T_5 - T_2)} \\ &= 100 \times \frac{(2460 - 1416) - (904 - 519)}{(2460 - 904)} \\ \eta_{C_v} &= 42.4\%\end{aligned}$$

With the temperature and pressures considered in this idealized example it is shown that by simply replacing the constant pressure combustor with a constant volume combustor the efficiency of the gas turbine was improved from 32.3% to 42.4%, and that the pressure ratio from the compressor inlet to the combustor outlet was increased from 6 to 9.3. It has been assumed that combustion actually took place stoichiometrically and that the hot combustion gases were expanded from the peak pressure, P_1 , to $P_9 = P_5$, and then mixed with excess air at P_5 until the mixture was at the desired turbine inlet temperature, T_6 .

A further increase in efficiency is possible if the air excess to combustion is compressed to pressure P_5 before mixing. The work available from expanding the combustion products from P_7 to $P_9 = P_5$ will be assumed available to compress the excess air. Reynst uses an improved Lenoir engine for this analysis [2]. The T-S diagram for this cycle is shown in figure 32.

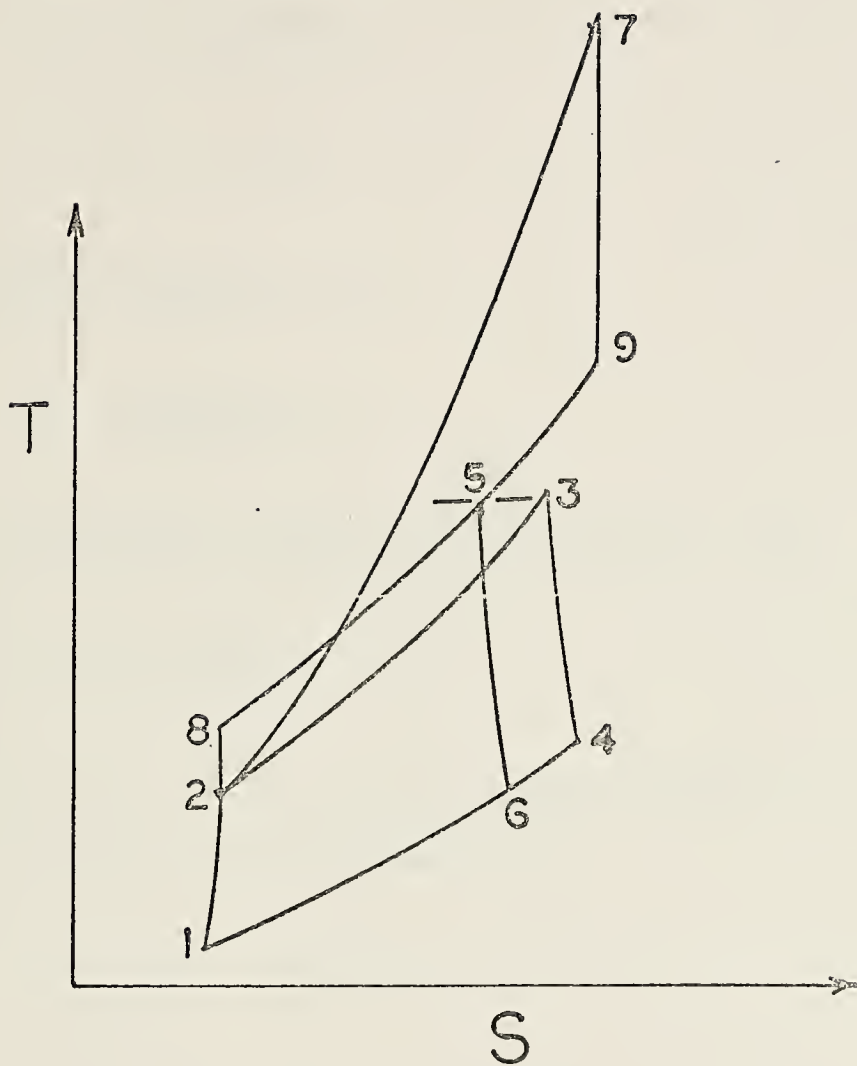


Figure 32. Temperature-Entropy diagram for gas turbine with pulse combustor in which expansion work from the combustor is used to compress cooling air.

Fuel is assumed to be burned stoichiometrically and λ pounds of excess air are thus required for one pound of primary air. The fuel/air ratio is approximately 1/15 for stoichiometric combustion.

The heat balance for $(\lambda+1)$ pounds of air is

$$(1+\lambda) C_P (T_3 - T_2) = Q_f$$

yielding an expression for λ

$$\lambda = \frac{Q_f}{C_p (T_3 - T_2)} - 1 \quad (21)$$

Peak pressure and temperature are obtained from

$$\Pi = \frac{P_7}{P_2} = \frac{T_7}{T_2}$$

An expression for Π is found by establishing the heat balance for one pound of stoichiometric air

$$C_V (T_7 - T_2) = Q_f$$

$$\Pi = \frac{Q_f}{C_V T_2} + 1 \quad (22)$$

A relation between λ and Π is obtained from

$$Q_f = (\Pi - 1) C_v T_2$$

$$\Pi = \frac{(\Pi - 1) C_v T_2}{(T_3 - T_2) C_p} - 1$$

$$\Pi - 1 = \frac{\gamma(\lambda + 1)(T_3 - T_2)}{T_2}$$

Finally

$$\frac{T_3}{T_2} = \frac{\Pi - 1}{\gamma(\lambda + 1)} + 1$$

Combustion products expand from peak pressure P_7 to P_9 , which is equal to P_5 . Excess air is compressed from P_2 to P_8 which is also equal to P_5 . The heat balance of combustion products and excess air, mixed at pressure P_5 , is given by,

$$C_p(T_9 - T_5) = \lambda C_p(T_5 - T_8) \quad (23)$$

For the isentropic expansion P_1 to P_9

$$\frac{T_9}{T_7} = \left(\frac{P_9}{P_7}\right)^{\frac{\gamma-1}{\gamma}} = \Pi T_2 \left(\frac{P_8}{\Pi P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

since $P_8 = P_9$ and $\Pi = \frac{T_7}{T_2} = \frac{P_7}{P_2}$.

Finally, it is found that

$$T_9 = T_8 \Pi^{\frac{1}{\gamma}} \quad (24)$$

Substituting for $D_5 = T_3$ and T_9 in the heat balance

$$T_8 \left(\Pi^{\frac{1}{\gamma}} + \lambda \right) = T_3 (1 + \lambda)$$

$$\frac{T_8}{T_2} = \frac{T_3}{T_2} \frac{(1 + \lambda)}{\left(\Pi^{\frac{1}{\gamma}} + \lambda \right)}$$

$$\frac{T_8}{T_2} = \left[\frac{\Pi - 1}{\gamma(\lambda + 1)} + 1 \right] \frac{(1 + \lambda)}{\left(\Pi^{\frac{1}{\gamma}} + \lambda \right)}$$

$$\frac{T_8}{T_2} = \frac{\Pi - 1 + \gamma + \gamma\lambda}{\gamma \left(\Pi^{\frac{1}{\gamma}} + \lambda \right)} \quad (25)$$

For P_8 from the isentropic relations

$$\frac{P_8}{P_2} = \left(\frac{T_8}{T_2} \right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{P_8}{P_2} = \left(\frac{\Pi - 1 + \gamma + \gamma\lambda}{\gamma \left(\Pi^{\frac{1}{\gamma}} + \lambda \right)} \right)^{\frac{\gamma}{\gamma - 1}} \quad (26)$$



Numerical example:

$$T_1 = 59^\circ\text{F} = 519^\circ\text{R}$$

$$T_2 = 444^\circ\text{F} = 904^\circ\text{R}$$

$$Q_f = 18,500 \text{ Btu/lb of fuel}$$

$$T_3 = T_5 = 2000^\circ\text{F} = 2460^\circ\text{R}$$

$$\frac{P_2}{P_1} = 6$$

$$f = \text{fuel/air ratio} = \frac{1}{15}$$

$$Q_m = f Q_f = \frac{18,500}{15} = 1233 \text{ Btu/lb of fuel/air mixture}$$

(fuel wt assumed small)

$$\lambda = \frac{1233}{0.24(2460 - 904)} - 1$$

$$\lambda = 2.30$$

$$\Pi = \frac{1233}{0.17(904)} + 1$$

$$\Pi = 9.023$$

$$\frac{T_8}{T_2} = \frac{9.023 + 1.4 - 1 + 1.4(2.30)}{1.4(9.023^{1/1.4} + 2.30)}$$

$$\frac{T_8}{T_2} = 1.27$$

$$\frac{P_8}{P_2} = (1.27)^{3.5}$$

$$\frac{P_8}{P_2} = 2.31$$



$$\frac{P_8}{P_1} = \frac{P_2}{P_1} \frac{P_8}{P_2} = 6(2.31)$$

$$\frac{P_8}{P_1} = 13.86$$

$$T_5 = T_3 = 2460^\circ\text{R}$$

$$P_5 = P_8 = 13.86 P_1 \quad \text{and} \quad P_6 = P_1$$

$$\frac{P_5}{P_6} = 13.86$$

$$\frac{T_5}{T_{6s}} = \left(\frac{P_5}{P_6}\right)^{\frac{\gamma-1}{\gamma}} = (13.86)^{\frac{0.4}{1.4}} = 2.12$$

$$T_{6s} = \frac{2460}{2.12} = 1160^\circ\text{R}$$

$$T_6 = T_5 = \eta_t(T_5 - T_{6s})$$

$$T_6 = 2460 - 0.9(2460 - 1160)$$

$$T_6 = 1290^\circ\text{R}$$

The thermal efficiency with the compression of excess air and constant volume combustion is

$$\eta_{c_v+P} = 100 \frac{(T_5 - T_6) - (T_2 - T_1)}{(T_5 - T_2)} = 100 \frac{(2460 - 1290) - (904 - 519)}{(2460 - 904)}$$

$$\eta_{c_v+P} = 50.4\%$$



Thus in this idealized example it is seen that substantial improvements are theoretically possible by the use of constant volume pulsating combustion. However, the mechanical complexities required to achieve true constant volume combustion could pose severe problems in a gas turbine and achieving the necessary flow rates for a practical machine in a combustor of sufficiently small size will certainly be difficult.

In South Africa, J. L. Muller has performed experimental work with pulsating combustors with the hope that they can be used in gas turbines. An analysis of his work is presented in the next section.

4. Theoretical Analysis of a Pulse Combuster for a Gas Turbine by J. L. Muller [8]

The theoretical analysis by Muller is of particular interest because it was done in support of experimental work and therefore more closely approximates actual conditions than the work of Reynst and the results of the analysis can be compared to experimental results. In his analysis Muller uses a polytropic combustion process to replace the ideal constant volume combustion process and assumes a polytropic expansion process. A pressure-volume diagram for the cycle assumed by Muller is shown in figure 33. It can be seen that it is quite similar to the Lenoir Cycle considered previously.

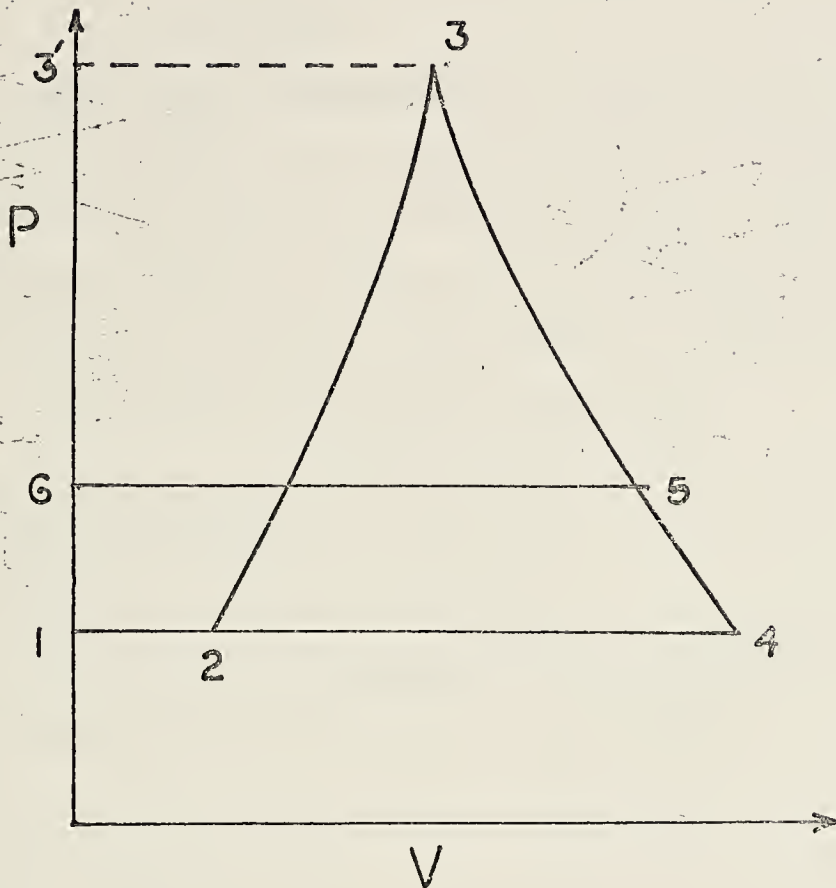


Figure 33. Pressure-Volume diagram for pulse combustor for a gas turbine with a polytropic combustion process.

The processes indicated on the diagram are

1-2 Intake

2-3 Polytropic combustion

3-4 Polytropic expansion

4-5 Slight recompression of exhaust gases
due to kinetic energy effects

5-6 Exhaust

Using this diagram Muller developed the following two analyses; one for no external work from the combustor, and another in which the available expansion work from the combustor is used to compress the cooling air (as in the third analysis of Reynst in the previous section [2].)

Work done by the gas in area 1433'

$$W_1 = \frac{n}{n-1} R(T_4 - T_3) \quad (27)$$

where n is polytropic parameter of expansion.

Work done on the gas in area 1233'

$$W_2 = - \frac{m}{1-m} R(T_3 - T_2) \quad (28)$$

where m is the polytropic parameter of combustion.

(A method for determining m and n will be given later.)

From these expressions it is possible to determine the net work done by the gas in area 234.

$$W_1 - W_2 = \frac{n}{1-n} R(T_4 - T_3) + \frac{m}{1-m} R(T_3 - T_2)$$

Defining

$$a \equiv \frac{m}{m-1}$$

and

$$b \equiv \frac{n}{n-1} ,$$

we get

$$W_1 - W_2 = -bR(T_4 - T_3) - aR(T_3 - T_2) .$$

The work done on the gas in area 1456 is

$$W_3 = - \frac{n}{1-n} R(T_5 - T_4) = bR(T_5 - T_4) . \quad (29)$$

There is no work output from the combustor and the work done by the gas in area 234, must be equated to the work done on the gas in area 1456 by the use of an efficiency α .

$$\alpha(W_1 - W_2) = W_3$$

$$\alpha[-bR(T_4 - T_3) - aR(T_3 - T_2)] = bR(T_5 - T_4) \quad (29a)$$

This can be written as:

$$\frac{T_5}{T_3} = \left(\frac{T_2}{T_3}\right)^{a/b} - \alpha \left\{ \left(\frac{T_2}{T_3}\right)^{a/b} - 1 + \frac{a}{b} \left(1 - \frac{T_2}{T_3}\right) \right\} \quad (30)$$

The pressure gain P_5/P_2 is obtained from

$$\frac{P_5}{P_2} = \left(\frac{T_5}{T_3}\right)^b \left(\frac{T_3}{T_2}\right)^a \quad (31)$$

Muller defines

$$B \equiv 1 - \alpha \left\{ 1 - \left(\frac{T_3}{T_2}\right)^{a/b} + \frac{a}{b} \left(\frac{T_3}{T_2}\right)^{a/b} \left(1 - \frac{T_2}{T_3}\right) \right\} \quad (32)$$

Thus P_5/P_2 can be rewritten as

$$\frac{P_5}{P_2} = B^b \quad (33)$$

In order to proceed with calculations it is necessary to determine the polytropic parameters m and n .

The following relationships can be obtained from the pressure-volume diagram

$$\frac{P_3}{P_2} = \left(\frac{T_3}{T_2}\right)^{\frac{m}{m-1}} \quad (34)$$

$$\frac{P_3}{P_4} = \frac{P_3}{P_2} = \left(\frac{T_3}{T_4}\right)^{\frac{n}{n-1}} \quad (35)$$

The heat added is

$$Q = (h_3 - h_2) + \frac{m}{1-m} R(T_3 - T_2) \quad (36)$$

Also

$$(h_3 - h_4) = \frac{n}{n-1} R(T_3 - T_4) \quad (37)$$

First the value of m will be determined.

$$\ln\left(\frac{P_3}{P_2}\right) = \ln\left(\frac{T_3}{T_2}\right)^{\frac{m}{m-1}}$$

$$\frac{m}{m-1} = \frac{\ln\left(\frac{P_3}{P_2}\right)}{\ln\left(\frac{T_3}{T_2}\right)} \quad (38)$$

$$Q = (h_3 - h_2) + \frac{\ln(P_3/P_2)}{\ln(T_3/T_2)} R(T_3 - T_2) \quad (39)$$

An assumption is now necessary for the pressure ratio P_3/P_2 . The type of fuel and fuel/air ratio determine the amount of heat per pound of air, Q . T_2 is combustor inlet temperature (or compressor outlet temperature). An iteration is then necessary to determine T_3 . Once T_3 is determined it is an easy matter to find m .

The value of n is found in a similar way from

$$(h_3 - h_4) = \frac{\ln(P_3/P_2)}{\ln(T_3/T_4)} R(T_3 - T_4) \quad (40)$$

An iteration is necessary to find T_4 . Once T_4 is known, n is found from

$$\frac{n}{n-1} = \frac{\ln(P_3/P_2)}{\ln(T_3/T_4)} \quad (41)$$

The efficiency factor, α , is found in the following manner. The following relationship is established.

$$-bR(T_4-T_3) - aR(T_3-T_2) = bR(T_5-T_4) \quad (42)$$

$$-a(T_3-T_2) = b[T_5-T_4+T_4-T_3]$$

$$(T_3-T_2) = \frac{b}{a}(T_3-T_5)$$

$$\frac{T_5}{T_2} = \frac{T_3}{T_2} - \frac{a}{b} \left(\frac{T_3}{T_2} - 1 \right) \quad (43)$$

T_3 is known from the previous calculations.

The pressure ratio P_5/P_2 is determined from

$$\frac{P_5}{P_2} = \frac{P_5}{P_3} \frac{P_3}{P_2} = \left(\frac{T_5}{T_2} \frac{T_2}{T_3} \right)^b \frac{P_3}{P_2}$$

This value of P_5/P_2 is too high in general and must be modified by an efficiency, α , such that the ratio P_5/P_2 agrees with experimental values. To do this we use equation (29a)

$$\alpha[-b(T_4-T_3) - a(T_3-T_2)] = b(T_5-T_4) \quad (44)$$

which can be rearranged as

$$\frac{T_5}{T_2} = \frac{T_4}{T_2} - \alpha \left\{ \frac{a}{b} \left(\frac{T_3}{T_2} - 1 \right) - \left(\frac{T_3}{T_2} - \frac{T_4}{T_2} \right) \right\} \quad (45)$$

The ratio T_4/T_2 is found from

$$\frac{T_4}{T_2} = \left(\frac{P_2}{P_3}\right)^{1/b} \frac{T_3}{T_2} \quad (46)$$

The value of α is then determined from equation 45.

If the cooling air is compressed isentropically by available expansion work from the combustor we have,

$$-b(T_4 - T_3) = a(T_3 - T_2) = b(T_5 - T_4) + \beta \left(\frac{\gamma}{\gamma - 1}\right) T_2 \left[\left(\frac{P_5}{P_2}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right]$$

This may be written as

$$\frac{P_5}{P_2} = (B - \beta E)^b \quad (47)$$

where

$$E = \frac{1}{a} \left(\frac{\gamma}{\gamma - 1}\right) \left(\frac{T_2}{T_3}\right) \frac{(b - a)}{b} \left[\left(\frac{P_5}{P_2}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right] \quad (48)$$

and

$$\beta \approx \frac{T_m - T_s}{T_2 - T_m} \quad (49)$$

where T_m is the Turbine Inlet Temperature.

According to Muller, equation 47 may be solved by assuming values for P_5/P_2 and T_m , calculating β and E , solving for P_5/P_2 , and iterating as required.

Numerical Example:

$$Q_f = 18,500 \text{ Btu/lb of fuel}$$

$$f = 0.05$$

$$h_2 = 126.18 \text{ Btu/lb}_m$$

$$T_2 = 528^\circ\text{R}$$

$$\frac{P_3}{P_2} = 2.5$$

$$q = Q_f f = 18,500 \times 0.05 = 927 \text{ Btu/lb of air (fuel wt} \ll 1)$$

$$q = (h_3 - h_2) + \frac{m}{1-m} R(T_3 - T_2) = (h_3 - h_2) - \frac{\ln(P_3/P_2)}{\ln(T_3/T_2)} (T_3 - T_2)$$

Assuming $T_3 = 3500^\circ\text{R}$ and $h_3 = 938.40 \text{ Btu/lb}_m$ for a starting point and iterating, we find:

$$T_3 = 4255^\circ\text{R}$$

and from

$$\frac{m}{m-1} = \frac{\ln(P_3/P_2)}{\ln(T_3/T_2)}$$

we determine

$$m = -0.783$$

Similarly for n.

$$h_3 - h_4 = \frac{\ln(P_3/P_2)}{\ln(T_3/T_4)} R(T_3 - T_4)$$

by iterating on T_4 and h_4 we find

$$T_4 = 3465^\circ\text{R}$$

and from

$$\frac{n}{n-1} = \frac{\ln(P_3/P_2)}{\ln(T_3/T_4)}$$

we find

$$n = 1.2889 \approx 1.29$$

$$\frac{T_5}{T_2} = \frac{T_3}{T_2} - \frac{m(1-n)}{n(1-m)} \left(\frac{T_3}{T_2} - 1 \right)$$

$$\frac{T_5}{T_2} = \frac{4255}{528} - \frac{(-0.783)(1 - 1.29)}{1.29(1 - 0.783)} \left(\frac{4255}{528} - 1 \right)$$

$$\frac{T_5}{T_2} = 7.36$$

Now

$$\frac{P_5}{P_2} = \left(\frac{T_5}{T_2} \frac{T_2}{T_3} \right)^{\frac{n}{n-1}} \frac{P_3}{P_2}$$

$$\frac{P_5}{P_2} = \left(\frac{7.36}{8.06} \right)^{\frac{1.29}{0.29}} (2.5) = 1.669$$

This value for P_5/P_2 is too high and an efficiency factor, α is used to reduce P_5/P_2 to 1.3.

$$\alpha \left[\frac{n}{1-n} R(T_4 - T_3) + \frac{m}{1-m} R(T_3 - T_2) \right] = - \frac{n}{1-n} R(T_5 - T_4)$$

which is rearranged to

$$\frac{T_5}{T_2} = \frac{T_4}{T_2} - \alpha \left\{ \frac{m(1-n)}{n(1-m)} \left(\frac{T_3}{T_2} - 1 \right) - \left(\frac{T_3}{T_2} - \frac{T_4}{T_2} \right) \right\} \quad [A]$$

From previous calculations

$$\frac{T_3}{T_2} = 8.06 \quad \frac{m(1-n)}{n(1-m)} = \frac{-0.783(1 - 1.29)}{1.29(1 + .783)} = 0.0987$$

and

$$\frac{T_4}{T_2} = \left(\frac{P_2}{P_3}\right)^{\frac{n-1}{n}} \left(\frac{T_3}{T_2}\right) = \left(\frac{1}{2.5}\right)^{\frac{0.29}{1.29}} (8.06) = 6.56$$

$$\frac{T_5}{T_2} = \left(\frac{P_5}{P_2} \frac{P_2}{P_3}\right)^{\frac{(n-1)}{n}} \frac{T_3}{T_2} = \left(\frac{1.3}{2.5}\right)^{\frac{0.29}{1.29}}$$

$$\frac{T_5}{T_2} = 6.96$$

Finally in [A]

$$6.96 = 6.56 - \alpha[0.0987(8.06 - 1) - (8.06 - 6.56)]$$

$$6.96 = 6.56 + 0.803$$

$$\alpha = \frac{6.96 - 6.56}{0.803}$$

$$\alpha = 0.498$$

B. WAVE PROCESSES

Proper operation of a pulsejet is heavily dependent upon the wave processes which occur during each cycle and it is these wave processes more than anything else which dictate the length to diameter ratio. The tube must be long enough to allow the waves to reflect and travel over the tube length and still have time for intake, proper combustion

and exhaust. Wave actions also dictate to a large degree the location of the fuel nozzles.

Basically the following processes can be identified [3]. At the instant of ignition, two waves are generated; a compression wave propagating toward the tube outlet and an expansion wave moving toward the inlet. The compression wave is reflected from the open tube end as an expansion wave and the original expansion wave reflects from the closed valves in the same sense; i.e., as an expansion wave. The reflected expansion waves lower the pressure in the tube below ambient, the valves open, and air flows into the tube. The expansion waves cause reduced pressure throughout the tube, including near the tail pipe, and as a result fresh air is drawn in through the tail pipe as well as through the valves.

The expansion waves reflect from the open end as compression waves and travel forward through the tube, and tend to slow the air entering through the valves, thus permitting time for proper combustion. These compression waves also close the valves. The open tube end is seen to be essential to proper operation of a pulsejet.

This process can be studied in detail using one dimensional non-steady flow analysis, and the method of characteristics. Results are shown in figure 34. In this figure compression waves are indicated by solid lines and expansion waves by dashed lines.

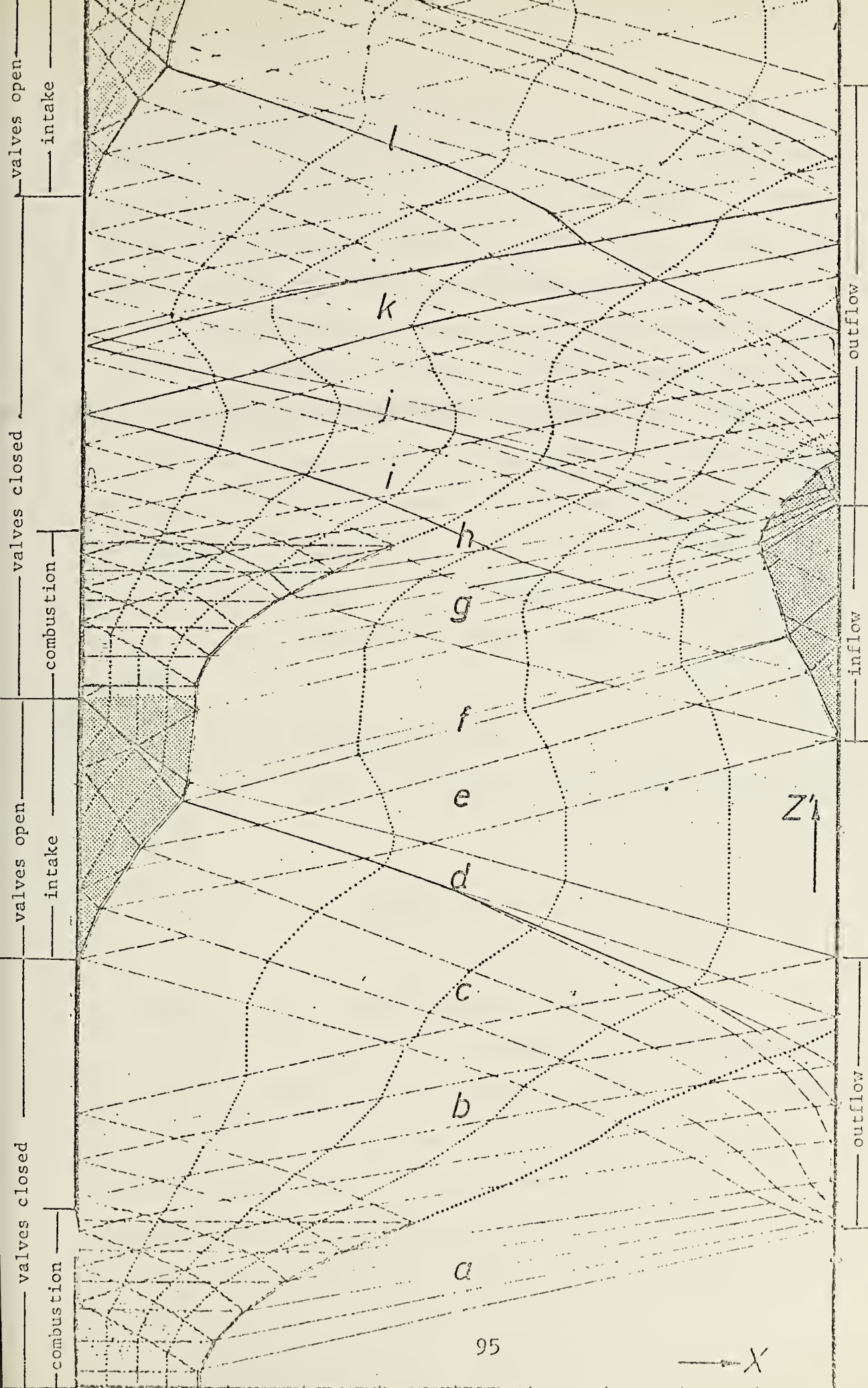


Figure 34. Wave processes in a pulsejet engine. (3)

Proper tube geometry is essential. A conically converging exit would cause a considerably weakened expansion wave or no expansion wave at all and would prevent proper valve operation. Conically diverging tubes reinforce the expansion waves and can be advantageous [3].

Proper wave patterns are also dependent upon the resistance of the valves to opening. If the valves open too easily then the waves are reflected in opposite sense (i.e., compression as expansion) and the pattern required for proper operation is thus interrupted. This was a problem in the V-1 engine at higher speeds when ram pressure was sufficient to overcome the valve resistance, and it was this effect which was the reason the V-1 was limited to relatively low speeds.

C. PERFORMANCE CHARACTERISTICS

The thermodynamic efficiency of the simple Lenoir cycle is given by

$$\eta_{th} = 1 - \gamma \frac{(\Pi)^{1/\gamma} - 1}{\Pi - 1}$$

for instantaneous combustion [2].

If finite combustion is included, but approximated by a linear combustion line on the P-v diagram [3] a somewhat more complicated expression is obtained for efficiency. The resulting efficiencies for various inlet temperatures and peak pressure to inlet pressure ratios are displayed in figure 35, showing that, at most, thermal efficiencies of

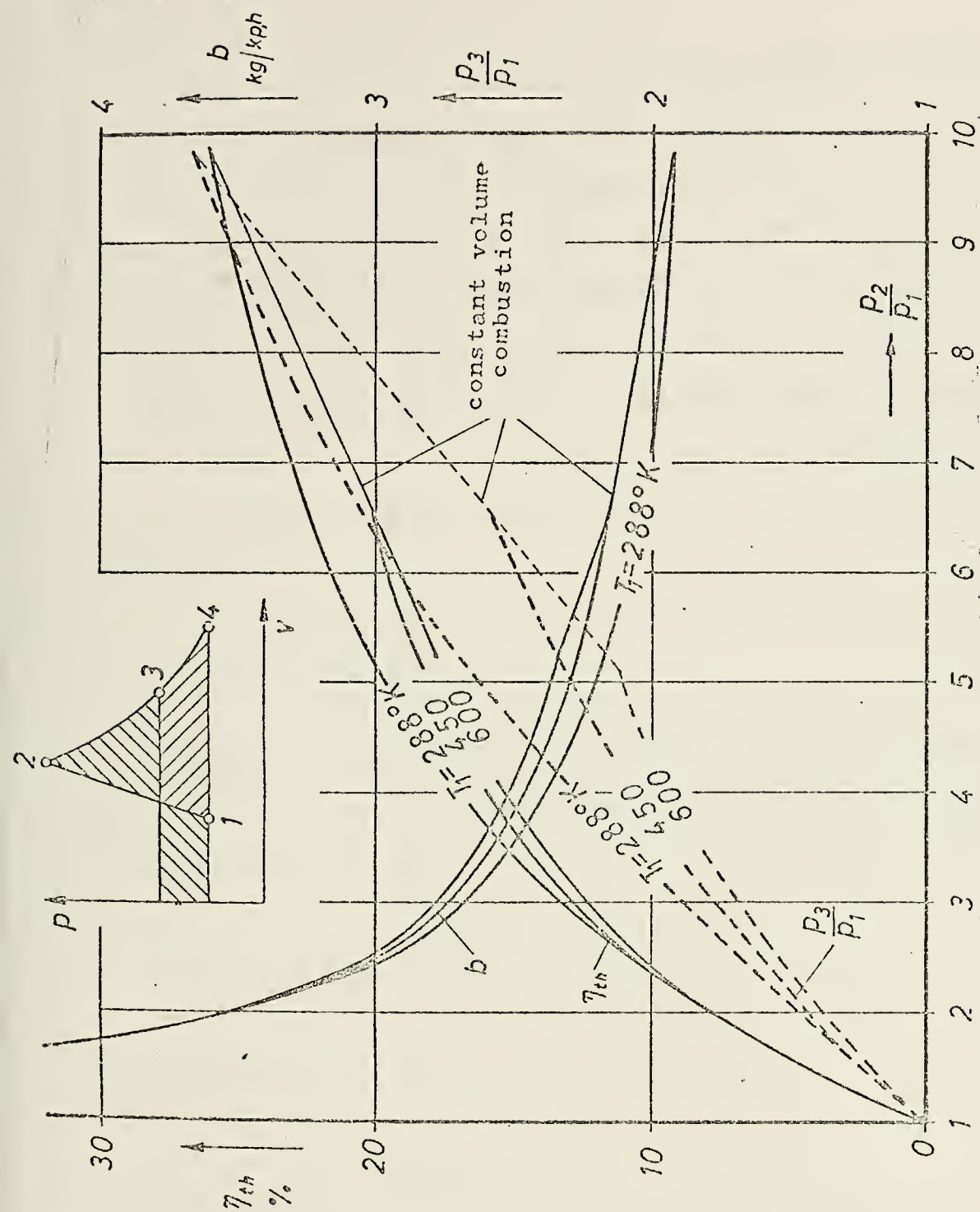


Figure 35. Efficiency of Lenoir cycle with stoichiometric combustion. (3)

up to 25% can be expected. From the analysis of Reynst theoretical efficiencies of up to 40% are obtained when considering the simple Lenoir cycle.

Of course, several losses occur in the engine, such as losses due to incomplete combustion, heat losses to surroundings, friction losses between fluid and wall, and losses due to non-uniform velocity distribution, and the efficiencies computed by Reynst are therefore higher than can be expected in an actual engine.

In order to compute thrust and specific fuel consumption, it is assumed that the useful energy from the fuel is equal to the increase in the kinetic energy of the combustion products leaving the engine.

$$Q \eta_{th} = \frac{m W_c^2}{2}$$

In addition the effects of friction, mixing of flows, and other losses must be accounted for and the above equation is modified as follows:

$$Q(\eta_{th})_{\eta_i} = \frac{m W_c^2}{2}$$

Solving for the average exit flow velocity W_c

$$W_c = \frac{2 Q \eta_{th} \eta_i}{m}$$

m in the above equation contains the combustion products plus the air entering the exit through backflow. The ratio

of the mass of this additional air to the mass of the primary combustion products is usually between 0.25 and 0.5.

Experimental data indicates that η_1 is usually between 0.2 and 0.3 [15].

The static thrust is then obtained from

$$T = \dot{m} W_c$$

The characteristic engine dimensions can be estimated in the following manner: The thrust coefficient,

$$C_T = \frac{T}{PS} ,$$

is introduced,

where: T = thrust

P = atmospheric pressure

S = nozzle cross sectional area

This thrust coefficient was found to be between 0.25 and 0.35. Hence, assuming a value of C_T and knowing the required thrust we obtain the cross sectional area of the nozzle. The engine length then is usually 8 to 10 times the nozzle diameter. The engine pulsation frequency can be estimated by treating the engine as an organ pipe open at one end. Hence, the frequency (realizing that $v\lambda = c$)

$$v = \frac{c}{4L}$$

$$c = \sqrt{g_c \gamma RT}$$

where: λ = wave length
and v = frequency
and c = speed of sound

D. THE IGNITION MECHANISM

In the past, several theories were advanced to explain the ignition mechanism in pulse-jet tubes.

In 1933, Reynst proposed that the mechanics of ignition were closely connected with the flow structure of the mixture and this led to the development of the "Reynst combustion pot," (fig. 8). Fresh air is drawn in from the annulus around the mouth of the chamber and a hollow cylindrical flow column is formed. Reynst suggested that this inflow is laminar and that this accelerated laminar flow column forms a growing vortex ring which prevents turbulent mixture of the inflow with the hot residual exhaust gases. The laminar flow prevents immediate ignition. After the inflow slows down, the column separates at the mouth of the chamber and the vortex breaks, thus permitting rapid mixing with the hot residual gases finally resulting in rapid ignition [2].

Schmidt discovered in 1937 that the tubes with which he was experimenting would continue to ignite without a spark if the proper valve area was chosen. He assumed that this automatic ignition was caused by a shock wave reflected from the open end of the tube back into the combustible mixture [1].

Military interest in the pulse jet inspired increased efforts in Germany during World War II. The Argus Motor Company received a pulse jet development contract. Under this contract, Diedrich [1] developed a new fuel injection system which improved the performance of the Schmidt-tube significantly. In the course of this work, Diedrich came to the conclusion that ignition was caused by residual hot gases and that the Argus-tube and Schmidt-tube therefore were based on a different operating principle.

During this same period, Staab [1] performed additional investigations on a tube equipped with viewing ports. He observed residual flames during aspiration and thus gave support to Diedrich's assumption.

Recent work by Zhuber-Okrog [3] substantially confirms the ignition-mechanism first postulated by Diedrich and Staab. Zhuber-Okrog has demonstrated that residual flames are required for continued automatic operation and that a flame-holding device is therefore required. Zhuber-Okrog's work is examined in more detail in Section IV.A. and V.B..

E. NOISE AND VIBRATION

While pulsejets offer the advantages of simplicity and low cost they do have some disadvantages, not the least of which are noise and vibration. Recent work has indicated that while these two problems can be severe, they are not insurmountable.

A group in England, led by F. E. J. Briffa, has published the results of a study they conducted in which the exhausts of two pulsating combustors were combined in order to reduce noise emission [16]. It was determined that the pressure patterns in a pulsating combustor are regular and fluctuate between positive and negative, and that if the amplitude of these fluctuations could be reduced a much lower noise level could be achieved. Further, it was felt that this could be done by phasing two pulse combustors so that they operated 180° out of phase. If the units were operating at the same frequency and pressure amplitudes, substantial noise reduction was theoretically possible.

Out of phase operation was achieved by interference operation, and fluid logic operation. Interference operation was used with three types of units; a Quarter wave tube, a Helmholtz tube and a Schmidt-tube.

Interference operation is achieved by connecting pulse combustors together at their open ends where there is a velocity antinode and a pressure node. According to Briffa, the two tubes will then operate 180° out of phase automatically. A schematic of this configuration is shown in figure 36.

Fluid logic operation results when phasing is achieved by use of a control unit which senses pressures in the adjacent tubes and sends fuel to the units so that they operate out of phase.

The results of these experiments indicate that the noise level of pulsejets can be reduced substantially. For example,

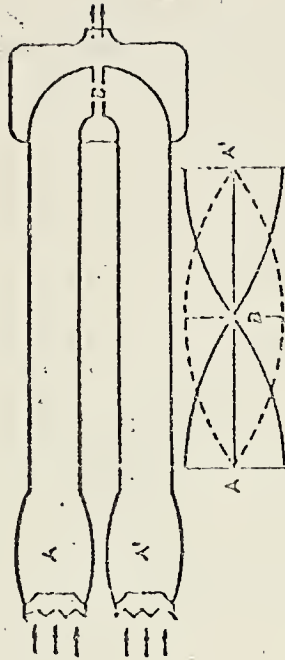


Figure 36. Interference operation of two pulsejets for noise reduction. (16)

the coupled Schmidt-tubes reduced the overall noise level from 113 DB to 82 DB without the use of an absorption silencer. Further results showed that the noise of a quarter wave resonator was easier to reduce than the noise of a Helmholtz resonator because the quarter wave resonator had a more regular pressure wave.

Further experimental study was conducted by Hanby and Brown [19] with single combustors, combustors coupled at the exit, and with combustors with reduced exit diameters. It was found that the configuration changes changed not only the noise levels, but internal pressure amplitude as well. Reducing the exit pipe diameter reduces both noise and pressure amplitude in the combustor, and hence performance. Coupling the combustors resulted in nearly doubled internal pressure amplitudes but no "spectacular" [17] noise reductions. However, twice as much fuel could be burned for the same noise emission.

In all configurations tested by Hanby and Brown, noise reduction was accompanied by a drop in performance. The results of Hanby and Brown experiments are shown in Table II [17].

A silent combustor of pulsating design has been built and operated by the Foster Wheeler Corporation of New Jersey. An interim report on its performance was presented at The First International Symposium of Pulsating Combustion in 1971 [18].

TABLE 2

Sound Pressure Level and Internal Pressure Amplitude
for Various Configurations [17]

Configuration	Broad Band SPL dB	Maximum RMS Pressure Amplitude in Combustor (P.S.I.)	I $\times 10^{-3}$	E $\times 10^{-4}$
a) Single combustor	112.4	1.84	5.2	0.3
b) Two combustors side by side	115.6	1.84	5.2	0.29
c) Two combustors coupled	116.3	3.43	18.2	0.34
d) as a) with 1 3/8" exit	106.7	0.92	1.3	0.08
e) as c) with 1 7/8" exit	115.7	2.68	10.1	0.30
f) as c) with 1 3/8" exit	114.1	1.98	6.1	0.21

The burner was self-aspirating, used aerodynamic valves, and operated in a silent mode with no reverse flow through the inlet. Silencing was accomplished by "moving the combustion region away from the region of the pressure antinode by using a high velocity air-jet at the inlet" [18]. This device was intended for use in industrial applications. Many questions about its operation and development work were continuing at the time of the interim report.

VI. POTENTIAL APPLICATIONS

A. PRESSURE GAIN COMBUSTION

In a series of theoretical studies, Reynst made a strong case for the use of pulsating combustion to increase the thermodynamic efficiency of the conventional gas turbine cycle [2]. These theoretical considerations prompted several investigators to verify the potential of pulsating combustion experimentally. The most detailed of these experiments seem to be those of Muller [2], Servanty [11], and Kentfield [12].

Muller achieved a pressure gain in his experiments, though the gain was less than his theoretical analysis predicted. Muller believed that further improvement was possible and eventually he would be able to equal, or perhaps exceed, his predicted values.

The work at SNECMA by Servanty with aerodynamically valved units showed a pressure gain of 1% representing an efficiency increase of 6 to 8% when compared to the 5 to 7% pressure loss in conventional gas turbine combustion chambers. This improvement provides incentive for further work, especially for small units operating at low compressor pressure ratios.

Certainly, at the moment, it appears difficult to make a high airflow rate pulsating combustor with no moving parts without its overall size becoming excessive for application

to a gas turbine. The SNECMA work indicates that pulsating combustion is presently limited to units below 800 horsepower.

B. HELICOPTER APPLICATION

The application of a pulsejet engine for helicopter propulsion was studied with considerable enthusiasm in the 1950's by several companies, including American Helicopter Co., McDonnell Aircraft Company, and others. Excessive noise and high fuel consumption, were factors which led to abandoning these projects. There has apparently been only one recent attempt to apply pulsejet propulsion to a helicopter, an unmanned surveillance helo which was built by the Naval Weapons Laboratory at Dahlgren, Va. [19]. The pulsejet used was a scaled down version of the 7.5 diameter engine developed by American Helicopter Company. The well known difficulties of operating pulsejets at higher speeds may have contributed to the disappointing performance of this scaled down engine and it may be that some of the German work on high subsonic and supersonic pulsejets might be used to overcome some of these difficulties. However, it seems that the application of pulsejets to helicopter propulsion is now limited to unmanned helicopters due to the noise problem.

A different application might be found using a number of miniature U-shaped valveless pulsejets, of the Fairchild-Hiller type, embedded in the span of a helicopter rotor for circulation control and thrust production. The circulation control rotor-principle is presently being investigated by

the Naval Ship Research and Development Center. It is based on the recognition that circulation control by tangential blowing over a rounded trailing edge is more efficient than other schemes. The purpose of this tangential blowing is to reenergize the boundary layer and thereby delay separation which would otherwise be caused by the adverse pressure gradient near the trailing edge. The Coanda effect causes the jet sheet to remain attached to the surface thus controlling the aft stagnation point by the strength of the blown air (fig. 37) [20]. The important point is that a small amount of blowing causes a large change in section lift coefficient.

Present circulation control rotors receive their air supply from a separate compressor through ducting within the blades. A recent proposal by M. F. Platzer of the U. S. Naval Postgraduate School indicates that the installation of several miniature pulsejets distributed along the rotor span might provide a simpler method of circulation control [21].

C. AUXILIARY POWER AND ENGINE STARTER UNITS

The feasibility of the pulsejet for auxiliary power generation was recently shown by Messerschmitt-Boelkow-Blohm GMBH in Germany [10]. Advantages of their pulsating APU are low cost (since a compressor is not required), ruggedness, and unsusceptibility to high intake temperatures. Disadvantages are high noise and vibration levels.

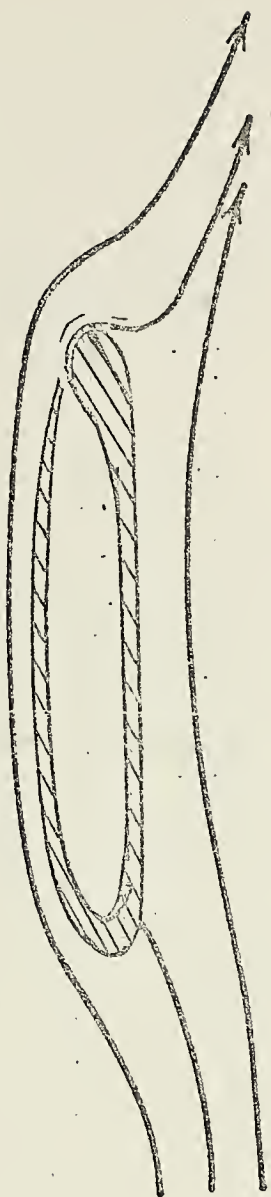


Figure 37. Circulation control schematic. (20)

Another application of the pulsejet engine is as a starter unit for turbine engines. A resonant combustor turbine starter was developed by Rocketdyne in 1966 [23]. In 1965 Aldag [24] developed two starter units, one similar to the well known Dynajet (which is primarily a model airplane engine) and a second mechanically valved unit for helicopter rotors. As before, low weight and low cost were definite advantages but high fuel consumption and noise were disadvantages.

D. DIRECT LIFT PROPULSION

The feasibility of using the pulsejet as a high performance lift engine for VTOL applications was studied extensively in the early 1960's by Fairchild Hiller [5]. Pulse reactors of several sizes were constructed and tested to determine the effect of the various engine parameters, and a typical unit is shown in figure 10. Thrust specific fuel consumptions as low as 0.9pph/pound of thrust, thrust to weight ratio as high as 12 to 1, and thrust to volume ratios as high as 150 pounds per cubic ft. were achieved. By comparison, the Rolls-Royce RB-162-81 lift engine for the VFW VAK-191B V/STOL aircraft has a thrust to weight ratio of 14.4 and a thrust to volume ratio of 290 pounds per cubic foot.

The tests also demonstrated rapid control response, a throttling range from 25% to full throttle, and good starting, durability, and maintenance characteristics. A unique feature of this lift propulsion system is its insensitivity to exhaust gas and foreign object ingestion.

In addition to the relatively high thrust to weight ratio and good specific fuel consumption, there are no moving parts. This system should therefore have a low initial cost and simple, low cost maintenance. Further development and application seem warranted. Of course, the noise problem virtually limits use to military systems, but recent noise alleviation methods discussed in Section 5.5 could prove beneficial and could make the pulsejet more attractive as a lift engine.

E. REMOTELY PILOTED VEHICLES

Recent improvements in modern air defenses demand corresponding improvement in penetration capability in order for an attacking force to maintain effectiveness at a low loss rate. Pulse jets could be used to power an inexpensive remotely piloted vehicle (RPV) designed to compound the enemy's air defense problem. Such an RPV would require high subsonic speed and a capability for maneuvering. It could be used as a decoy, chaff dispenser, electronic jammer, or for carrying a reconnaissance package, and it could supplement more expensive recoverable RPV's and manned aircraft [22].

If the costs were kept low enough, large numbers of RPV's could be used to penetrate enemy air space in an attempt to force commitment of missiles and draw anti-aircraft fire. Perhaps a few could be equipped with warheads to provide an incentive to down the RPV's even if recognized as decoys [22].

It now appears to be possible to build a pulsejet to operate in the speed range required for such a mission which would have acceptable performance, no moving parts, be rugged and reliable, and have a low cost. Noise, usually a problem, could even be an asset for such a mission.

F. OTHER APPLICATIONS

Numerous applications other than those previously mentioned in this report have been proposed for pulsating combustion devices. Examples are use as air heaters, water heaters, deicers, dryers, and conveyors. Further uses include heating of viscous crude oil in the ground so that the oil may be recovered more easily, hole boring, and pile driving.

Pulsejets and pulsating combustors have been made to operate on a wide variety of fuels from gaseous hydrogen to pulverized coal.

Evidently the best uses for pulsejets and pulse combustors have yet to be discovered since they have not yet achieved widespread use.

VII. SUMMARY AND CONCLUSIONS

The purpose of this paper was to survey the literature relative to pulsejets published after 1968 when a report entitled "The Feasibility of Pulsejets and Intermittent Combustion Devices as Modern Propulsion Power Plants" was published by the Naval Weapons Center, China Lake, California [25]. Since then considerable research has been conducted on pulsejets and pressure gain combustors. Most of this work has been in foreign countries, notably Germany, England, France, Canada, South Africa, and Russia. In 1971, an international symposium on Pulsating Combustion was held at the University of Sheffield, Sheffield, England. Both these development programs and the symposium indicate renewed interest in the pulsating combustion process and the conviction by a number of researchers that there is an inherent potential for its application.

One possible reason that early pulsejets have not lived up to their potential is that the development of a mathematical model of a pulsejet is extremely complex and even today an entirely adequate theoretical study has never been completed. But construction of a pulsejet is a relatively simple task and therefore many have been built without sufficient knowledge of the effects of the many parameters.

It is obvious that a lack of understanding of the unsteady flow and combustion processes prevents, at the present time,

prediction and improvement of pulsejet performance.

Theoretically, a great potential for improvement exists.

Emphasis should be directed toward developing a method for introducing the heat input in a very short time interval so that the process is very nearly constant volume. This could be done by improved combustion techniques or perhaps by introducing the heat in an entirely new way, such as lasers or electrical discharge. Lasers, of course, would increase cost and complexity significantly and would eliminate most benefits of a pulsejet. But, have all possible methods of heat input been considered or investigated? Probably not and perhaps new thinking is needed here.

The frequency of operation needs to be increased so that the noise and vibration problems are alleviated.

Further development of aerodynamic valves, of operation of clusters of pulsejets, of operation at high forward flight speeds, and of a hybrid "pulsejet to ramjet" system are needed. A hybrid pulsejet-ramjet could cover a wide speed range from zero to high supersonic mach numbers.

The extreme simplicity and resulting low cost of this fascinating propulsion device should provide considerable incentive for its development.

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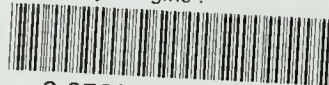
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